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McGRAW-HILL SERIES IN CHEMICAL ENGINEERING
SIDNEY D. KIRKPATRICK, *Consulting Editor*

Manual for Process Engineering Calculations

McGRAW-HILL SERIES IN CHEMICAL ENGINEERING

Sidney D. Kirkpatrick, *Consulting Editor*

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BUILDING FOR THE FUTURE OF A PROFESSION

Fifteen prominent chemical engineers first met in New York more than thirty years ago to plan a continuing literature for their rapidly growing profession. From industry came such pioneer practitioners as Leo H. Baekeland, Arthur D. Little, Charles L. Reese, John V. N. Dorr, M. C. Whitaker, and R. S. McBride. From the universities came such eminent educators as William H. Walker, Alfred H. White, D. D. Jackson, J. H. James, J. F. Norris, Warren K. Lewis, and Harry A. Curtis. H. C. Parmelee, then editor of *Chemical & Metallurgical Engineering*, served as chairman and was joined subsequently by S. D. Kirkpatrick as consulting editor.

After several meetings, this Editorial Advisory Committee submitted its report to the McGraw-Hill Book Company in September, 1925. In it were detailed specifications for a correlated series of more than a dozen text and reference books, including a chemical engineers' handbook and basic textbooks on the elements and principles of chemical engineering, on industrial applications of chemical synthesis, on materials of construction, on plant design, on chemical-engineering economics. Broadly outlined, too, were plans for monographs on unit operations and processes and on other industrial subjects to be developed as the need became apparent.

From this prophetic beginning has since come the McGraw-Hill Series in Chemical Engineering, which now numbers about thirty-five books. More are always in preparation to meet the ever-growing needs of chemical engineers in education and in industry. In the aggregate these books represent the work of literally hundreds of authors, editors, and collaborators. But no small measure of credit is due the pioneering members of the original committee and those engineering educators and industrialists who have succeeded them in the task of building a permanent literature for the classical engineering profession.

THE SERIES

Aries and Newton—*Chemical Engineering Cost Estimation*
Badger and Banchero—*Introduction to Chemical Engineering*
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Kirkbride—*Chemical Engineering Fundamentals*
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Lewis, Radasch, and Lewis—*Industrial Stoichiometry*
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Mantell—*Industrial Electrochemistry*
McAdams—*Heat Transmission*
McCabe and Smith—*Unit Operations of Chemical Engineering*
Nelson—*Petroleum Refinery Engineering*
Perry (Editor)—*Chemical Business Handbook*
Perry (Editor)—*Chemical Engineers' Handbook*
Peters—*Elementary Chemical Engineering*
Pierce—*Chemical Engineering for Production Supervision*
Rhodes, F. H.—*Technical Report Writing*
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Robinson and Gilliland—*Elements of Fractional Distillation*
Schmidt and Marlies—*Principles of High-polymer Theory and Practice*
Schweyer—*Process Engineering Economics*
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Sherwood and Reed—*Applied Mathematics in Chemical Engineering*
Shreve—*The Chemical Process Industries*
Smith—*Chemical Engineering Kinetics*
Smith—*Introduction to Chemical Engineering Thermodynamics*
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Vilbrandt—*Chemical Engineering Plant Design*
Walker, Lewis, McAdams, and Gilliland—*Principles of Chemical Engineering*
Wilson and Ries—*Principles of Chemical Engineering Thermodynamics*
Wilson and Wells—*Coal, Coke, and Coal Chemicals*
Winding and Hasche—*Plastics, Theory and Practice*

Manual for Process Engineering Calculations

■ ■ ■ ■ ■ ■ ■ ■ ■ ■ ■ ■ ■ ■ ■ ■ ■

LOYAL CLARKE

Chemical Engineer, Day & Zimmermann, Inc. Formerly with
Celanese Corporation of America, Petroleum Chemicals, Inc., and
The United States Bureau of Mines

McGraw-Hill Book Company, Inc.
New York Toronto London 1947

MANUAL FOR PROCESS ENGINEERING CALCULATIONS

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THE MAPLE PRESS COMPANY, YORK, PA.

This book is dedicated to

STELLA S. CLARKE

in partial acknowledgment
of an important role
in its preparation.

EDITOR'S PREFACE

The Chemical Plant Library has been planned to provide a group of reference books in the chemical field. The aim of the series is to present a comprehensive and unified body of knowledge—mainly for self-help and reference.

The Library will appeal to many types of readers. It will be of bread-and-butter value to all: the so-called "practical man," the research engineer, the chemist or engineer in a process industry plant. They may brush up or learn something as needs arise. It will help the practical man compete with his college-trained associates. It will assist younger men in broadening their fields. It will keep older men up-to-date with latest developments.

The Library was not planned for classroom study as textbooks. Higher mathematics such as calculus and difficult equations have been avoided wherever possible.

There are five books in the series. They deal with (1) chemical calculations, (2) economics, (3) unit operations, (4) chemical process industries, and (5) materials of construction.

This group of books has been made possible largely through the cooperation of the several authors to whom the editor wishes to express his thanks.

JAMES A. LEE

NEW YORK, N. Y.
September, 1950

PREFACE

This book is intended as a convenience for chemical engineers and others who may be required to present quick answers without adequate time for recourse to the many comprehensive texts and reference books. It is not intended as a substitute for either. An accurate and complete answer to almost any problem will require more information than is contained here. Industry is full of equipment that has been installed because someone timidly ventured "It seems about the right size." To increase the accuracy in this kind of guesswork every process engineer has his own file of useful data charts and whatnot. These he makes as brief as possible for ready reference. This is essentially such a set of notes; it is only a start toward a handy set of working data for rapid-process calculations. The hope is that it may be found useful.

The presentation of data includes discussion of methods of application to process design calculations but does not give a complete exposition of the basic underlying theories. The novice is, accordingly, cautioned of the danger in the use of data beyond the range of validity; he is, moreover, admonished of the desirability of making estimates by more than one method, using basic data from different sources.

This book includes compilations of data from numerous sources, and every effort has been made to give full credit where it is due. Inclusion of some previously unpublished material was made possible by the generous cooperation of Mr. James P. Kneubuhl of the Fluor Corporation, Ltd., Mr. F. W. Laverty of the Clark Brothers Co., Inc., Mr. Stanley A. Tucker, Associate Editor of *Electrical World* and Mr. V. deP. Gerbereaux of the Worthington Pump and Machinery Corporation. Mr. M. H. Douthitt assisted materially in the preparation of the entire manuscript. Mr. William Soherr, the late Mr. J. L. Schlitt, Dr. M. C. Molstad, Mr. George H. Black, Mr. L. P. Rockenbach, Dr. G. B. Carpenter, and Mr. C. R. Williams have contributed valuable suggestions. Indebtedness is acknowledged to the references given and to the various individuals who have given assistance. Last, but not least, the generosity of the management of Petroleum Chemicals, Inc., in granting permission to prepare and publish this book is appreciated.

Suggestions for future improvement of the text will be welcomed.

LOYAL CLARKE

ROSLYN, PA.
September, 1950

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CHAPTER A

PERSPECTIVE

This chapter indulges in a discussion of the nature and philosophy of process engineering, presents some general references, and outlines the nomenclature used.

1. Philosophical Notes

a. Process Engineers and Definitions.—Philosophy and definitions are hopelessly intertwined. Tell me your definitions and I will tell you your philosophy. One ordinarily thinks of an engineer as one who deals with precisely defined terms suited for detailed analyses of problems. This is true, but it should not be overemphasized. As "go-between," dealing with assistant operators and vice-presidents in charge of research, all engineers must put up with vaguely defined terms since the pipe fitter does not understand the precise terminology of engineering, and the plant superintendent—who does—refuses to be bothered. It is appropriate that this should be so. Very specific terms are essential for getting down to details; general terms are needed, if consideration of the broad aspects of a problem are not to be clouded by useless detail. To put it another way, engineering problems require flexible thinking, which is favored by the inclusion of flexible terms in the vocabulary.

The division of science and engineering into various fields is necessary because a lifetime is insufficient for an individual to become conversant with more than a small fraction of the sum total of knowledge. It is also important that the division be a liberal one. An attempt to group into definite compartments would fail because many gaps would result. Moreover, the scientists and engineers would not tolerate such a restriction of their activities. It is better to define the centers of interest and allow each individual to expand in as many directions as his ability permits.

The process engineer's principal duty is to translate the findings of the laboratory into a basic commercial plant design ready for the designers and estimators to complete the final mechanical design and cost estimates. His chief weapons are the slide rule, graph sheets, sketch pads, reference books, a sharp pencil, and his background of experience, education, and common sense. A good education in chemical engineering is essential, and some additional mathematics, physics, chemistry, and mechanical engineering thrown in do no harm. Equally essential is common sense; process engineering is an art as well as a science. There are usually so many ways of manufacturing anything, that the engineer must confine his attention to only the most promising, in order to keep within the allotted time.

b. Operating against Investment Costs.—Modern methods have progressed to the point where a plant may easily be overmechanized. The question of balance between investment and operating costs requires careful consideration.

In public utilities, rates are usually set by commissions who base sales prices on just rates on capital invested. This, together with the stability of demand, favors high investments. In other industries the vagaries of market prices of raw materials and products often do not permit investment on a long-term basis so that a plant that cannot "pay out" in a short time is considered a doubtful venture. The sum of annual interest, depreciation, maintenance, taxes, and overhead charges made by the cost accountant is usually at 20 per cent of the gross capital outlay. In making very rough estimates, the costs of major items may be added together, but the sum will represent only a small fraction of the total outlay, which must include piping, wiring, sewers, foundations, yard structures, various construction overheads, etc. The inclusion of these items may *more than triple* the total.

c. The Case for Inefficiency.—The process engineer, whether trained originally as a physicist, mechanical engineer, chemist, or chemical engineer, is a scientist and is inclined to make a fetish of efficiency. Frequently, therefore, he has the natural tendency always to choose apparatus and processes that give the highest engineering performance. The results achieved for each dollar expended is the true measure of industrial utility. By the choice of less efficient processes or equipment, the investment cost may often be lowered with no alarming increase in operating cost.

Consequently, the process engineer should avoid specifying heat exchangers with too close approach, steam turbines of very high efficiencies, etc. On the other hand, the use of added utilities also represents capital outlay in the power plant, water plant, and piping.

d. Sizing of Equipment.—If plant equipment is oversized, the investment is unnecessarily large. If equipment is too small, production suffers. Since it is often impossible to state capacities exactly, reasonable factors of safety for different types of equipment must be adopted. These factors depend on the relative uncertainties involved and on the costs of purchasing oversize equipment. They should, when possible, be adopted as a result of discussion between design engineers, process engineers, estimators, and those charged with operation. Only one thing will be stressed here: regardless of the method used in choosing the factors of safety, a summary of them for each piece of equipment should be recorded in one place. Hidden factors of safety introduced by one member of the staff may be overlooked by others and thereby compounded.

e. Process Control.—The process engineer can usually compute suitable flows for good operation. The whole process from there rises or falls on the ability to operate the plant at these flows. Consequently, simplicity in the control system and other factors favoring ease of operations are important considerations in choosing between competitive proposals.

f. The Case for Efficiency.—The preceding comment stresses simplicity and low cost as factors of first importance. There is no intent to disparage efficiency. The modern trend has been toward ever-increasing performance factors. An inefficient plant is not likely to be competitive in present-day industry. Usually the management would be glad to spend 7 or 8 per cent more to secure a machine of 5 per cent greater efficiency but would balk at double the cost.

To be most successful, the plant must combine efficiency and simplicity. This sounds like a difficult assignment, and it is. Usually, solutions are available and will be found, provided the various engineers on the project have imagination and are ever conscious of the need of securing the best performance with economy.

g. Process Calculations.—The first consideration is the over-all process: determining the quantity of products to be made and the raw materials required. This may be divided into a number of separate units. Finally, the process is broken down to *unit operations*. For many of these, standard equipment is employed, and methods of estimation based on theory and experience are available. These procedures are frequently sufficiently simple and standardized so that they may be employed without much knowledge of theory.

When new types of equipment are encountered, recourse must be made to the basic chemical, physical, and engineering principles before it can be stated whether any of the standard methods are applicable. A surprising number of problems may be wholly or partly solved by (1) material balances, (2) energy balances, (3) consideration of equilibrium conditions at key points, and (4) equipment performance factors. Material and energy balances are applicable to the whole process, any unit, any single piece of equipment, or any minute operation. A consideration of the mechanism is necessary to determine where close approaches to equilibrium are involved. Performance factors are certain only when experimentally determined, though analogies to other types of equipment may afford a guide. The twins, trial and error, are a great nuisance, but without them process engineers would be helpless in cases where recycles between units make everything dependent on everything else. Frequently something must be assumed in order to get started.

The process engineer should not complain because all roads are not paved. Rather he should rejoice that there are still frontiers affording the opportunity to use his ingenuity to the fullest extent.

2. General References

The beginning of each chapter gives a list of references pertaining to the particular subject. Here are listed some comprehensive texts which cover a number of fields of interest to process engineers. Only treatises in the English language are included.

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3. Nomenclature

An effort has been made throughout the book to define the symbols used in each equation on the same or at least on an adjacent page. Below are listed the more frequent symbols used throughout the book. The standards of the American Institute of Chemical Engineers have been used as the general basis. However, several changes were found necessary to prevent confusion.

A	Work content (Helmholz free energy); absorption factor
a	Activity
α	Ostwald coefficient of (gas) solubility
β	Bunsen coefficient of (gas) solubility; ratio of orifice to pipe diameter
C	Coefficient of discharge for orifices and nozzles
C_p	Heat capacity [Btu/(lb mole) (°F)] at constant pressure
C_v	Heat capacity [Btu/(lb mole) (°F)] at constant volume

c_p	Specific heat [Btu/(lb)(°F)] at constant pressure
c_v	Specific heat [Btu/(lb)(°F)] at constant volume
D	Diameter (larger of two)
d	Diameter (smaller of two); differential operator
Δ	Prefixed to indicate that value is change accompanying some process (*i.e.*, Δp would be a pressure drop)
E	Efficiency
e	Base of natural logarithms = 2.718
ϵ	Emissivity
F	Free energy (Lewis)
f	Fanning friction factor; fugacity; functional relationship
G	Mass velocity; moles/hr
g	Acceleration due to gravity
γ	Ratio of specific heats at constant pressure, volume
H	Heat content (enthalpy); Henry's-law constant in pressure units
h	Fluid head; heat content of liquid when gas = H
I	Liquid irrigation rate in packed columns
J	Mechanical equivalent of heat
K	Equilibrium constant for chemical reactions; coefficient of discharge from orifice including velocity of approach
k	Thermal conductivity; vaporization equilibrium constant = y/x
L	Latent heat of vaporization; length of pipe; mass (or mole) flow of liquid corresponding to G for gas in same system
l	Length or thickness
M	Flow of gas, standard cfm
m	Flow, gpm; molecular weight
μ	Viscosity; Joule-Thomson coefficient
N	Rpm; mole fraction (liquid or gas)
n	Number (as number of theoretical plates)
ν	Kinematic viscosity
P	Percentage
p	Pressure
π	Ratio of circle circumference to diameter = 3.1416
Q	Heat absorbed
R	Gas-law constant
r	Radius; compression ratio
ρ	Density
S	Entropy; specific gravity of gases (air = 1); stripping factor; length of stroke
s	Specific gravity of liquids (water = 1); entropy of liquid when gas = S
T	Absolute temperature (°R or °K)

t	Relative temperature (°F or °C)
U	Intrinsic (internal) energy; over-all coefficient of heat transfer
u	Velocity; mean velocity
V	Volume
W	Weight flow
w	Work (done by system)
X	Mole ratio, liquids
x	Mole fraction in liquid
Y	Expansion factor (for gases through orifices); mole ratio, gases
y	Mole fraction in gas
Z	Height above datum plane
z	Compressibility factor in reduced equation of state

CHAPTER B

NUMERICAL AND MATHEMATICAL DATA

1. Logarithms

Table B-1 gives four-place logarithms; Table B-2 gives four-place antilogarithms. Natural logarithms may be obtained by multiplying the common logarithms (to base 10) by 2.3026.

$$\begin{aligned} \ln x &= (\ln 10) \cdot \log x \\ &= 2.3026 \log x \end{aligned}$$

The table of antilogs may be used to evaluate exponentials as follows:

$$\begin{aligned} 10^x &= \text{antilog } x \\ e^x &= \text{antilog} \left(\frac{x}{2.3026}\right) \end{aligned}$$

TABLE B-1.—FOUR-PLACE LOGARITHMS

N.	0	1	2	3	4	5	6	7	8	9	Proportional parts				
											1	2	3	4	5
10	0000	0043	0086	0128	0170	0212	0253	0294	0334	0374	4	8	12	17	21
11	0414	0453	0492	0531	0569	0607	0645	0682	0719	0755	4	8	11	15	19
12	0792	0828	0864	0899	0934	0969	1004	1038	1072	1106	3	7	10	14	17
13	1139	1173	1206	1239	1271	1303	1335	1367	1399	1430	3	6	10	13	16
14	1461	1492	1523	1553	1584	1614	1644	1673	1703	1732	3	6	9	12	15
15	1761	1790	1818	1847	1875	1903	1931	1959	1987	2014	3	6	8	11	14
16	2041	2068	2095	2122	2148	2175	2201	2227	2253	2279	3	5	8	11	13
17	2304	2330	2355	2380	2405	2430	2455	2480	2504	2529	2	5	7	10	12
18	2553	2577	2601	2625	2648	2672	2695	2718	2742	2765	2	5	7	9	12
19	2788	2810	2833	2856	2878	2900	2923	2945	2967	2989	2	4	7	9	11
20	3010	3032	3054	3075	3096	3118	3139	3160	3181	3201	2	4	6	8	11
21	3222	3243	3263	3284	3304	3324	3345	3365	3385	3404	2	4	6	8	10
22	3424	3444	3464	3483	3502	3522	3541	3560	3579	3598	2	4	6	8	10
23	3617	3636	3655	3674	3692	3711	3729	3747	3766	3784	2	4	5	7	9
24	3802	3820	3838	3856	3874	3892	3909	3927	3945	3962	2	4	5	7	9
25	3979	3997	4014	4031	4048	4065	4082	4099	4116	4133	2	3	5	7	9
26	4150	4166	4183	4200	4216	4232	4249	4265	4281	4298	2	3	5	7	8
27	4314	4330	4346	4362	4378	4393	4409	4425	4440	4456	2	3	5	6	8
28	4472	4487	4502	4518	4533	4548	4564	4579	4594	4609	2	3	5	6	8
29	4624	4639	4654	4669	4683	4698	4713	4728	4742	4757	1	3	4	6	7
30	4771	4786	4800	4814	4829	4843	4857	4871	4886	4900	1	3	4	6	7
31	4914	4928	4942	4955	4969	4983	4997	5011	5024	5038	1	3	4	6	7
32	5051	5065	5079	5092	5105	5119	5132	5145	5159	5172	1	3	4	5	7
33	5185	5198	5211	5224	5237	5250	5263	5276	5289	5302	1	3	4	5	6
34	5315	5328	5340	5353	5366	5378	5391	5403	5416	5428	1	3	4	5	6
35	5441	5453	5465	5478	5490	5502	5514	5527	5539	5551	1	2	4	5	6
36	5563	5575	5587	5599	5611	5623	5635	5647	5658	5670	1	2	4	5	6
37	5682	5694	5705	5717	5729	5740	5752	5763	5775	5786	1	2	3	5	6
38	5798	5809	5821	5832	5843	5855	5866	5877	5888	5899	1	2	3	5	6
39	5911	5922	5933	5944	5955	5966	5977	5988	5999	6010	1	2	3	4	5
40	6021	6031	6042	6053	6064	6075	6085	6096	6107	6117	1	2	3	4	5
41	6128	6138	6149	6160	6170	6180	6191	6201	6212	6222	1	2	3	4	5
42	6232	6243	6253	6263	6274	6284	6294	6304	6314	6325	1	2	3	4	5
43	6335	6345	6355	6365	6375	6385	6395	6405	6415	6425	1	2	3	4	5
44	6435	6444	6454	6464	6474	6484	6493	6503	6513	6522	1	2	3	4	5
45	6532	6542	6551	6561	6571	6580	6590	6599	6609	6618	1	2	3	4	5
46	6628	6637	6646	6656	6665	6675	6684	6693	6702	6712	1	2	3	4	5
47	6721	6730	6739	6749	6758	6767	6776	6785	6794	6803	1	2	3	4	5
48	6812	6821	6830	6839	6848	6857	6866	6875	6884	6893	1	2	3	4	4
49	6902	6911	6920	6928	6937	6946	6955	6964	6972	6981	1	2	3	4	4
50	6990	6998	7007	7016	7024	7033	7042	7050	7059	7067	1	2	3	3	4
51	7076	7084	7093	7101	7110	7118	7126	7135	7143	7152	1	2	3	3	4
52	7160	7168	7177	7185	7193	7202	7210	7218	7226	7235	1	2	2	3	4
53	7243	7251	7259	7267	7275	7284	7292	7300	7308	7316	1	2	2	3	4
54	7324	7332	7340	7348	7356	7364	7372	7380	7388	7396	1	2	2	3	4
N.	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5

TABLE B-1.—FOUR-PLACE LOGARITHMS (*Continued*)

N.	0	1	2	3	4	5	6	7	8	9	Proportional parts				
											1	2	3	4	5
55	7404	7412	7419	7427	7435	7443	7451	7459	7466	7474	1	2	2	3	4
56	7482	7490	7497	7505	7513	7520	7528	7536	7543	7551	1	2	2	3	4
57	7559	7566	7574	7582	7589	7597	7604	7612	7619	7627	1	2	2	3	4
58	7634	7642	7649	7657	7664	7672	7679	7686	7694	7701	1	1	2	3	4
59	7709	7716	7723	7731	7738	7745	7752	7760	7767	7774	1	1	2	3	4
60	7782	7789	7796	7803	7810	7818	7825	7832	7839	7846	1	1	2	3	4
61	7853	7860	7868	7875	7882	7889	7896	7903	7910	7917	1	1	2	3	4
62	7924	7931	7938	7945	7952	7959	7966	7973	7980	7987	1	1	2	3	3
63	7993	8000	8007	8014	8021	8028	8035	8041	8048	8055	1	1	2	3	3
64	8062	8069	8075	8082	8089	8096	8102	8109	8116	8122	1	1	2	3	3
65	8129	8136	8142	8149	8156	8162	8169	8176	8182	8189	1	1	2	3	3
66	8195	8202	8209	8215	8222	8228	8235	8241	8248	8254	1	1	2	3	3
67	8261	8267	8274	8280	8287	8293	8299	8306	8312	8319	1	1	2	3	3
68	8325	8331	8338	8344	8351	8357	8363	8370	8376	8382	1	1	2	3	3
69	8388	8395	8401	8407	8414	8420	8426	8432	8439	8445	1	1	2	3	3
70	8451	8457	8463	8470	8476	8482	8488	8494	8500	8506	1	1	2	2	3
71	8513	8519	8525	8531	8537	8543	8549	8555	8561	8567	1	1	2	2	3
72	8573	8579	8585	8591	8597	8603	8609	8615	8621	8627	1	1	2	2	3
73	8633	8639	8645	8651	8657	8663	8669	8675	8681	8686	1	1	2	2	3
74	8692	8698	8704	8710	8716	8722	8727	8733	8739	8745	1	1	2	2	3
75	8751	8756	8762	8768	8774	8779	8785	8791	8797	8802	1	1	2	2	3
76	8808	8814	8820	8825	8831	8837	8842	8848	8854	8859	1	1	2	2	3
77	8865	8871	8876	8882	8887	8893	8899	8904	8910	8915	1	1	2	2	3
78	8921	8927	8932	8938	8943	8949	8954	8960	8965	8971	1	1	2	2	3
79	8976	8982	8987	8993	8998	9004	9009	9015	9020	9025	1	1	2	2	3
80	9031	9036	9042	9047	9053	9058	9063	9069	9074	9079	1	1	2	2	3
81	9085	9090	9096	9101	9106	9112	9117	9122	9128	9133	1	1	2	2	3
82	9138	9143	9149	9154	9159	9165	9170	9175	9180	9186	1	1	2	2	3
83	9191	9196	9201	9206	9212	9217	9222	9227	9232	9238	1	1	2	2	3
84	9243	9248	9253	9258	9263	9269	9274	9279	9284	9289	1	1	2	2	3
85	9294	9299	9304	9309	9315	9320	9325	9330	9335	9340	1	1	2	2	3
86	9345	9350	9355	9360	9365	9370	9375	9380	9385	9390	1	1	2	2	3
87	9395	9400	9405	9410	9415	9420	9425	9430	9435	9440	0	1	1	2	2
88	9445	9450	9455	9460	9465	9469	9474	9479	9484	9489	0	1	1	2	2
89	9494	9499	9504	9509	9513	9518	9523	9528	9533	9538	0	1	1	2	2
90	9542	9547	9552	9557	9562	9566	9571	9576	9581	9586	0	1	1	2	2
91	9590	9595	9600	9605	9609	9614	9619	9624	9628	9633	0	1	1	2	2
92	9638	9643	9647	9652	9657	9661	9666	9671	9675	9680	0	1	1	2	2
93	9685	9689	9694	9699	9703	9708	9713	9717	9722	9727	0	1	1	2	2
94	9731	9736	9741	9745	9750	9754	9759	9763	9768	9773	0	1	1	2	2
95	9777	9782	9786	9791	9795	9800	9805	9809	9814	9818	0	1	1	2	2
96	9823	9827	9832	9836	9841	9845	9850	9854	9859	9863	0	1	1	2	2
97	9868	9872	9877	9881	9886	9890	9894	9899	9903	9908	0	1	1	2	2
98	9912	9917	9921	9926	9930	9934	9939	9943	9948	9952	0	1	1	2	2
99	9956	9961	9965	9969	9974	9978	9983	9987	9991	9996	0	1	1	2	2
N.	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5

TABLE B-2.—ANTILOGARITHMS

	0	1	2	3	4	5	6	7	8	9	Proportional parts				
											1	2	3	4	5
.00	1000	1002	1005	1007	1009	1012	1014	1016	1019	1021	0	0	1	1	1
.01	1023	1026	1028	1030	1033	1035	1038	1040	1042	1045	0	0	1	1	1
.02	1047	1050	1052	1054	1057	1059	1062	1064	1067	1069	0	0	1	1	1
.03	1072	1074	1076	1079	1081	1084	1086	1089	1091	1094	0	0	1	1	1
.04	1096	1099	1102	1104	1107	1109	1112	1114	1117	1119	0	1	1	1	1
.05	1122	1125	1127	1130	1132	1135	1138	1140	1143	1146	0	1	1	1	1
.06	1148	1151	1153	1156	1159	1161	1164	1167	1169	1172	0	1	1	1	1
.07	1175	1178	1180	1183	1186	1189	1191	1194	1197	1199	0	1	1	1	1
.08	1202	1205	1208	1211	1213	1216	1219	1222	1225	1227	0	1	1	1	1
.09	1230	1233	1236	1239	1242	1245	1247	1250	1253	1256	0	1	1	1	1
.10	1259	1262	1265	1268	1271	1274	1276	1279	1282	1285	0	1	1	1	1
.11	1288	1291	1294	1297	1300	1303	1306	1309	1312	1315	0	1	1	1	2
.12	1318	1321	1324	1327	1330	1334	1337	1340	1343	1346	0	1	1	1	2
.13	1349	1352	1355	1358	1361	1365	1368	1371	1374	1377	0	1	1	1	2
.14	1380	1384	1387	1390	1393	1396	1400	1403	1406	1409	0	1	1	1	2
.15	1413	1416	1419	1422	1426	1429	1432	1435	1439	1442	0	1	1	1	2
.16	1445	1449	1452	1455	1459	1462	1466	1469	1472	1476	0	1	1	1	2
.17	1479	1483	1486	1489	1493	1496	1500	1503	1507	1510	0	1	1	1	2
.18	1514	1517	1521	1524	1528	1531	1535	1538	1542	1545	0	1	1	1	2
.19	1549	1552	1556	1560	1563	1567	1570	1574	1578	1581	0	1	1	1	2
.20	1585	1589	1592	1596	1600	1603	1607	1611	1614	1618	0	1	1	1	2
.21	1622	1626	1629	1633	1637	1641	1644	1648	1652	1656	0	1	1	1	2
.22	1660	1663	1667	1671	1675	1679	1683	1687	1690	1694	0	1	1	2	2
.23	1698	1702	1706	1710	1714	1718	1722	1726	1730	1734	0	1	1	2	2
.24	1738	1742	1746	1750	1754	1758	1762	1766	1770	1774	0	1	1	2	2
.25	1778	1782	1786	1791	1795	1799	1803	1807	1811	1816	0	1	1	2	2
.26	1820	1824	1828	1832	1837	1841	1845	1849	1854	1858	0	1	1	2	2
.27	1862	1866	1871	1875	1879	1884	1888	1892	1897	1901	0	1	1	2	2
.28	1905	1910	1914	1919	1923	1928	1932	1936	1941	1945	0	1	1	2	2
.29	1950	1954	1959	1963	1968	1972	1977	1982	1986	1991	0	1	1	2	2
.30	1995	2000	2004	2009	2014	2018	2023	2028	2032	2037	0	1	1	2	2
.31	2042	2046	2051	2056	2061	2065	2070	2075	2080	2084	0	1	1	2	2
.32	2089	2094	2099	2104	2109	2113	2118	2123	2128	2133	0	1	1	2	2
.33	2138	2143	2148	2153	2158	2163	2168	2173	2178	2183	0	1	1	2	2
.34	2188	2193	2198	2203	2208	2213	2218	2223	2228	2234	1	1	2	2	3
.35	2239	2244	2249	2254	2259	2265	2270	2275	2280	2286	1	1	2	2	3
.36	2291	2296	2301	2307	2312	2317	2323	2328	2333	2339	1	1	2	2	3
.37	2344	2350	2355	2360	2366	2371	2377	2382	2388	2393	1	1	2	2	3
.38	2399	2404	2410	2415	2421	2427	2432	2438	2443	2449	1	1	2	2	3
.39	2455	2460	2466	2472	2477	2483	2489	2495	2500	2506	1	1	2	2	3
.40	2512	2518	2523	2529	2535	2541	2547	2553	2559	2564	1	1	2	2	3
.41	2570	2576	2582	2588	2594	2600	2606	2612	2618	2624	1	1	2	2	3
.42	2630	2636	2642	2649	2655	2661	2667	2673	2679	2685	1	1	2	2	3
.43	2692	2698	2704	2710	2716	2723	2729	2735	2742	2748	1	1	2	2	3
.44	2754	2761	2767	2773	2780	2786	2793	2799	2805	2812	1	1	2	3	3
.45	2818	2825	2831	2838	2844	2851	2858	2864	2871	2877	1	1	2	3	3
.46	2884	2891	2897	2904	2911	2917	2924	2931	2938	2944	1	1	2	3	3
.47	2951	2958	2965	2972	2979	2985	2992	2999	3006	3013	1	1	2	3	3
.48	3020	3027	3034	3041	3048	3055	3062	3069	3076	3083	1	1	2	3	3
.49	3090	3097	3105	3112	3119	3126	3133	3141	3148	3155	1	1	2	3	4
	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5

TABLE B-2.—ANTILOGARITHMS (*Continued*)

	0	1	2	3	4	5	6	7	8	9	Proportional parts				
											1	2	3	4	5
.50	3162	3170	3177	3184	3192	3199	3206	3214	3221	3228	1	1	2	3	4
.51	3236	3243	3251	3258	3266	3273	3281	3289	3296	3304	1	1	2	3	4
.52	3311	3319	3327	3334	3342	3350	3357	3365	3373	3381	1	1	2	3	4
.53	3388	3396	3404	3412	3420	3428	3436	3443	3451	3459	1	2	2	3	4
.54	3467	3475	3483	3491	3499	3508	3516	3524	3532	3540	1	2	2	3	4
.55	3548	3556	3565	3573	3581	3589	3597	3606	3614	3622	1	2	2	3	4
.56	3631	3639	3648	3656	3664	3673	3681	3690	3698	3707	1	2	2	3	4
.57	3715	3724	3733	3741	3750	3758	3767	3776	3784	3793	1	2	3	3	4
.58	3802	3811	3819	3828	3837	3846	3855	3864	3873	3882	1	2	3	3	4
.59	3890	3899	3908	3917	3926	3936	3945	3954	3963	3972	1	2	3	4	5
.60	3981	3990	3999	4009	4018	4027	4036	4046	4055	4064	1	2	3	4	5
.61	4074	4083	4093	4102	4111	4121	4130	4140	4150	4159	1	2	3	4	5
.62	4169	4178	4188	4198	4207	4217	4227	4236	4246	4256	1	2	3	4	5
.63	4266	4276	4285	4295	4305	4315	4325	4335	4345	4355	1	2	3	4	5
.64	4365	4375	4385	4395	4406	4416	4426	4436	4446	4457	1	2	3	4	5
.65	4467	4477	4487	4498	4508	4519	4529	4539	4550	4560	1	2	3	4	5
.66	4571	4581	4592	4603	4613	4624	4634	4645	4656	4667	1	2	3	4	5
.67	4677	4688	4699	4710	4721	4732	4742	4753	4764	4775	1	2	3	4	5
.68	4786	4797	4808	4819	4831	4842	4853	4864	4875	4887	1	2	3	5	6
.69	4898	4909	4920	4932	4943	4955	4966	4977	4989	5000	1	2	3	5	6
.70	5012	5023	5035	5047	5058	5070	5082	5093	5105	5117	1	2	3	5	6
.71	5129	5140	5152	5164	5176	5188	5200	5212	5224	5236	1	2	4	5	6
.72	5248	5260	5272	5284	5297	5309	5321	5333	5346	5358	1	2	4	5	6
.73	5370	5383	5395	5408	5420	5433	5445	5458	5470	5483	1	3	4	5	6
.74	5495	5508	5521	5534	5546	5559	5572	5585	5598	5610	1	3	4	5	6
.75	5623	5636	5649	5662	5675	5689	5702	5715	5728	5741	1	3	4	5	7
.76	5754	5768	5781	5794	5808	5821	5834	5848	5861	5875	1	3	4	5	7
.77	5888	5902	5916	5929	5943	5957	5970	5984	5998	6012	1	3	4	5	7
.78	6026	6039	6053	6067	6081	6095	6109	6124	6138	6152	1	3	4	6	7
.79	6166	6180	6194	6209	6223	6237	6252	6266	6281	6295	1	3	4	6	7
.80	6310	6324	6339	6353	6368	6383	6397	6412	6427	6442	1	3	4	6	7
.81	6457	6471	6486	6501	6516	6531	6546	6561	6577	6592	2	3	5	6	8
.82	6607	6622	6637	6653	6668	6683	6699	6714	6730	6745	2	3	5	6	8
.83	6761	6776	6792	6808	6823	6839	6855	6871	6887	6902	2	3	5	6	8
.84	6918	6934	6950	6966	6982	6998	7015	7031	7047	7063	2	3	5	7	8
.85	7079	7096	7112	7129	7145	7161	7178	7194	7211	7228	2	3	5	7	8
.86	7244	7261	7278	7295	7311	7328	7345	7362	7379	7396	2	3	5	7	8
.87	7413	7430	7447	7464	7482	7499	7516	7534	7551	7568	2	4	5	7	9
.88	7586	7603	7621	7638	7656	7674	7691	7709	7727	7745	2	4	5	7	9
.89	7762	7780	7798	7816	7834	7852	7870	7889	7907	7925	2	4	6	7	9
.90	7943	7962	7980	7998	8017	8035	8054	8072	8091	8110	2	4	6	7	9
.91	8128	8147	8166	8185	8204	8222	8241	8260	8279	8299	2	4	6	8	9
.92	8318	8337	8356	8375	8395	8414	8433	8453	8472	8492	2	4	6	8	10
.93	8511	8531	8551	8570	8590	8610	8630	8650	8670	8690	2	4	6	8	10
.94	8710	8730	8750	8770	8790	8810	8831	8851	8872	8892	2	4	6	8	10
.95	8913	8933	8954	8974	8995	9016	9036	9057	9078	9099	2	4	6	8	10
.96	9120	9141	9162	9183	9204	9226	9247	9268	9290	9311	2	4	6	9	11
.97	9333	9354	9376	9397	9419	9441	9462	9484	9506	9528	2	4	6	9	11
.98	9550	9572	9594	9616	9638	9661	9683	9705	9727	9750	2	4	7	9	11
.99	9772	9795	9817	9840	9863	9886	9908	9931	9954	9977	2	5	7	9	11
	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5

2. Powers of Numbers

Figure B-1 permits the approximate estimation of powers and roots. Because of the large number of operations that can be performed on this single chart, it is likely to be confusing at first. Familiarity with it, however, will disclose its true simplicity.

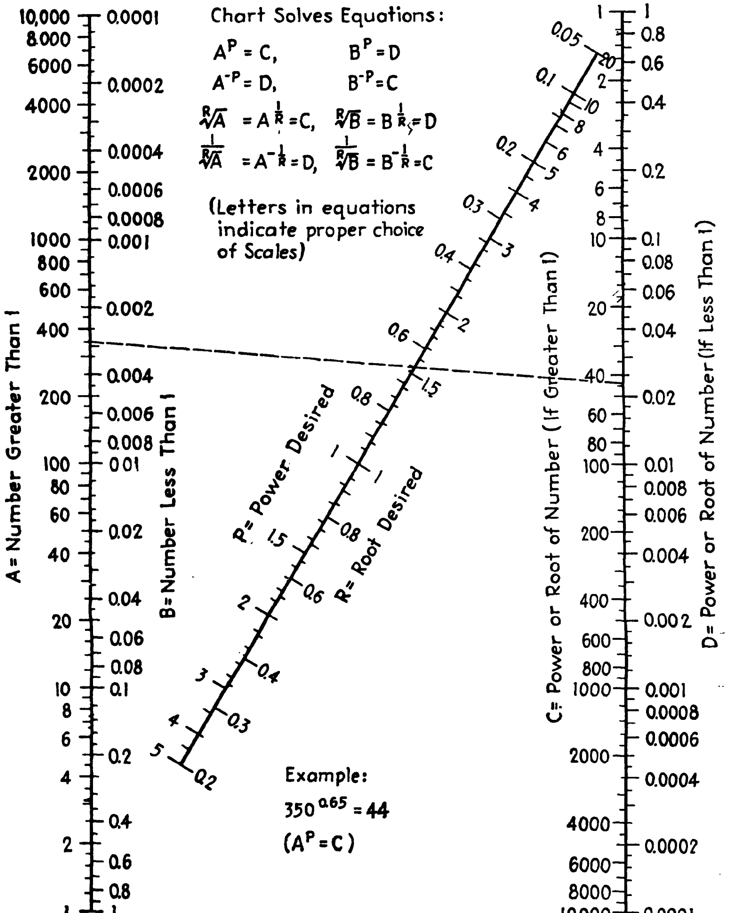


FIG. B-1.—Chart for estimating powers and roots.

3. Formulas for Area

Circle: $\frac{\pi}{4} \times (\text{diameter})^2 = 0.7854\ (\text{diameter})^2$

$\pi \times (\text{radius})^2 = 3.1416\ (\text{radius})^2$

Rectangle: Width × length.
Triangles:
Right angle = ½ product of two sides adjacent to right angle
Equilateral = 0.4330 × (side)^2
Surface of sphere: 3.1416 (diameter)^2

4. Formulas for Volume

Sphere: $\frac{\pi}{6}$ (diameter)^3 = 0.5236 (diameter)^3

Regular prism: Area of base × altitude

Cone: $\frac{\pi}{12}$ (diameter)^2 × altitude

Cylindrical tanks: See Tables B-3, B-4, and Fig. B-2.

TABLE B-3.—GALLONS PER INCH OF DEPTH IN VERTICAL CYLINDRICAL TANKS

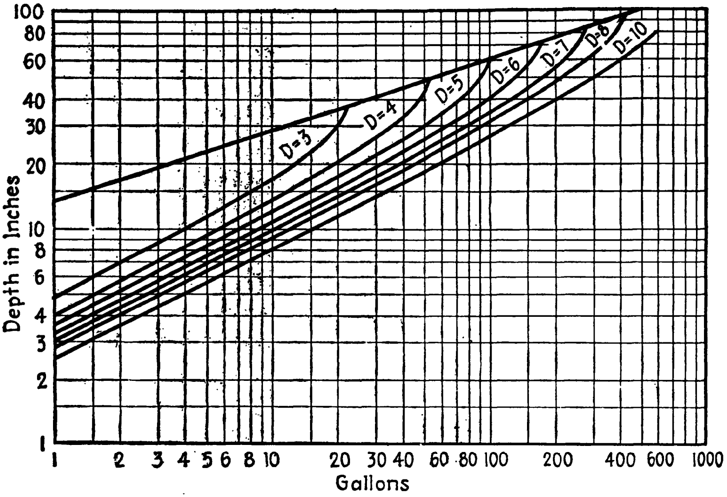
Diameter												
Ft	In.											
	0	1	2	3	4	5	6	7	8	9	10	11
	Gallons per inch											
0	.....	.....	.....	.....	.....	.....	0.12	0.17	0.22	0.28	0.34	0.41
1	0.49	0.58	0.67	0.77	0.87	0.98	1.10	1.23	1.36	1.50	1.65	1.80
2	1.96	2.12	2.30	2.48	2.67	2.86	3.06	3.27	3.48	3.70	3.93	4.16
3	4.41	4.66	4.91	5.17	5.44	5.72	6.00	6.29	6.58	6.88	7.20	7.51
4	7.85	8.16	8.50	8.84	9.19	9.55	9.91	10.28	10.66	11.05	11.44	11.84
5	12.24	12.65	13.07	13.50	13.93	14.36	14.81	15.26	15.72	16.19	16.66	17.14
6	17.63	18.12	18.62	19.12	19.64	20.16	20.69	21.22	21.76	22.31	22.86	23.42
7	24.0	24.6	25.2	25.7	26.3	26.9	27.5	28.3	28.1	29.4	30.0	30.7
8	31.3	32.0	32.6	33.3	34.0	34.7	35.4	36.1	36.8	37.5	38.2	38.9
9	39.6	40.4	41.1	41.9	42.6	43.4	44.2	45.0	45.8	46.5	47.4	48.2
10	49.0	49.8	50.6	51.4	52.3	53.1	54.0	54.8	55.7	56.6	57.5	58.4
11	59.2	60.1	61.0	62.0	62.9	63.8	64.8	65.7	66.6	67.6	68.6	69.5
12	70.3	71.5	72.5	73.5	74.5	75.5	76.5	77.5	78.6	79.6	80.6	81.7
13	82.7	83.8	84.9	86.0	87.0	88.1	89.2	90.3	91.4	92.6	93.7	94.8
14	96.0	97.1	98.3	99.4	100.6	101.8	102.9	104.1	105.3	106.5	107.7	108.9

TABLE B-4.—CAPACITIES OF HORIZONTAL CYLINDRICAL TANKS IN U.S. GALLONS
(Contents given for 1 ft of length, flat ends)
(Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York, 1941)

Diameter of tank, in.	Depth of liquid, in.																
	3	6	9	12	15	18	21	24	27	30	33	36	39	42	45	48	51
12	1.15	2.94	4.73	5.88													
18	1.45	3.86	6.61	9.36	11.77	13.22											
24	1.70	4.60	8.05	11.75	15.45	18.90	21.80	23.50									
30	1.91	5.23	9.27	13.72	18.36	23.00	27.45	31.49	34.81	36.72							
36	2.12	5.79	10.34	15.43	20.85	26.44	32.03	37.45	42.54	47.09	50.76	52.88					
42	2.28	6.31	11.31	16.97	23.07	29.46	35.99	42.51	48.90	55.00	60.66	65.66	69.69	71.97			
48	2.45	6.78	12.20	18.38	25.10	32.20	39.54	47.01	54.47	61.81	68.91	75.63	81.81	87.23	91.56	94.01	
54	2.60	7.22	13.04	19.68	26.97	34.72	42.80	51.08	59.49	67.90	76.18	84.26	92.01	99.30	105.94	111.76	116.38
60	2.75	7.64	13.82	20.91	28.72	37.06	45.82	54.88	64.11	73.45	82.78	92.01	101.07	109.83	118.17	125.98	133.07
66	2.89	8.04	14.56	22.07	30.37	39.28	48.65	58.39	68.42	78.59	88.87	99.14	109.31	119.34	129.08	138.45	147.36
72	3.02	8.42	15.26	23.17	31.92	41.36	51.32	61.71	72.45	83.41	94.54	105.76	116.98	128.11	139.07	149.81	160.20
78	3.15	8.78	15.94	24.21	33.41	43.34	53.86	64.87	76.27	87.97	99.90	111.97	124.12	136.27	148.34	160.27	171.97
84	3.26	9.12	16.57	25.24	34.85	45.24	56.29	67.87	79.91	92.30	104.98	117.85	130.87	143.95	157.03	170.05	182.92
90	3.43	9.46	17.20	26.20	36.21	47.05	58.61	70.75	83.39	96.43	109.81	123.46	137.28	151.22	165.25	179.27	193.21
96	3.50	9.79	17.80	27.13	37.52	48.81	60.84	73.52	86.73	100.39	114.44	128.79	143.40	158.17	173.07	188.01	202.95
102	3.61	10.10	18.37	28.01	39.00	50.49	62.99	76.18	89.94	104.20	118.89	133.92	149.25	164.81	180.53	196.36	212.25
108	3.71	10.39	18.94	28.90	40.03	52.14	65.09	78.74	93.04	107.87	123.17	138.87	154.89	171.19	187.71	204.37	221.15

TABLE B-4.—CAPACITIES OF HORIZONTAL CYLINDRICAL TANKS IN U.S. GALLONS (*Continued*)

Diameter of tank, in.	Depth of liquid, in.																
	54	57	60	63	66	69	72	75	78	81	84	87	90	93	96	102	108
12																	
18																	
24																	
30																	
36																	
42																	
48																	
54	118.98																
60	139.25	144.14	146.89														
66	155.66	163.17	169.69	174.84	177.73												
72	170.16	179.60	188.35	196.26	203.10	208.50	211.52										
78	183.37	194.38	204.90	214.83	224.03	232.30	239.46	245.09	248.24								
84	195.60	207.99	220.03	231.61	242.66	253.05	262.66	271.33	278.78	284.64	287.90						
90	207.03	220.68	234.06	247.10	259.74	271.88	283.44	294.28	304.29	313.29	321.03	327.06	330.49				
96	217.85	232.62	247.23	261.58	275.63	289.29	302.50	315.18	327.21	338.50	348.89	358.22	366.23	372.52	376.02		
102	228.12	243.95	259.67	275.23	290.56	305.59	320.28	334.54	348.30	361.49	373.99	385.48	396.47	406.11	414.38	424.48	
108	238.05	254.75	271.53	288.19	304.71	321.01	337.03	352.73	368.03	382.86	397.16	410.81	423.76	435.87	447.00	465.51	475.90



Constructed from Doolittle Formula, *Ind. Eng. Chem.*, March, 1928.

V (both ends) $= 0.0009328h^2(3r - h)$, gal.
h = depth, in.
r = radius of tank, in.
In curves D = diameter of tank, ft

FIG. B-2.—Volumes of (two) bulged or dished ends of horizontal cylindrical tanks. (*Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York,* 1941.) This chart is to be used in conjunction with Table B-4 to secure volumes of horizontal tanks with dished ends.

5. Integrals and Differentials

TABLE B-5.—DIFFERENTIALS AND INTEGRALS

Function, f	Derivative, $\dfrac{df}{dx}$	Integral, $\int f\,dx$
ax	a	$\dfrac{a}{2}x^2$
ax^n	anx^{n-1}	$\dfrac{ax^{n+1}}{n+1}$ (unless $n = -1$)
uv	$u\dfrac{dv}{dx} + v\dfrac{du}{dx}$	
$\dfrac{u}{v}$	$\dfrac{v\dfrac{du}{dx} - u\dfrac{dv}{dx}}{v^2}$	
$\dfrac{a}{bx+c}$	$-\dfrac{ab}{(bx+c)^2}$	$\dfrac{a}{b}\ln(bx+c)$
$\dfrac{1}{a+bx+cx^2}$	$-\dfrac{b+2cx}{(a+bx+cx^2)^2}$	$\dfrac{2}{\sqrt{4ac-b^2}}\tan^{-1}\left(\dfrac{2cx+b}{\sqrt{4ac-b^2}}\right)$ or, $\dfrac{2}{\sqrt{b^2-4ac}}\ln\left(\dfrac{2cx+b-\sqrt{b^2-4ac}}{2cx+b+\sqrt{b^2-4ac}}\right)$
e^{ax}	ae^{ax}	$\dfrac{1}{a}e^{ax}$
a^{bx}	$ba^{bx}\ln(bx)$	$\dfrac{a^{bx}}{b\ln(bx)}$
$\ln ax$	$\dfrac{a}{x}$	$x\ln ax - x$
$\log ax$	$\dfrac{a}{2.30259x}$	$\dfrac{x}{2.30259}\log ax - \dfrac{x}{2.30259}$

NOTE: $\ln x$ = logarithm of x to the base e
$\log x$ = logarithm of x to the base 10
$\tan^{-1} x$ = *principal* angle, in radians, whose tangent is x

6. Approximations

$$(1 \pm a)^n = 1 \pm na \qquad \text{(when } a \text{ is small)}$$

$$(1 \pm a)^m(1 \pm b)^n = 1 \pm ma \pm nb \qquad \text{(when } a \text{ and } b \text{ are small)}$$

$$\sqrt{mn} = \frac{n+m}{2} \qquad \text{(when } m - n \text{ is small)}$$

For small angles expressed in radians:

$$\theta = \sin\theta = \tan\theta$$

CHAPTER C

CONVERSION TABLES

The engineer constantly uses a wide variety of units in his calculations. This chapter gives data for the interconversion of units frequently used by American chemists and engineers. No effort has been made to include units in common usage in other countries or to comment on small differences between different versions of the same unit. For *very precise* work it is, of course, necessary to specify the particular variety of calorie, Btu, watt, volt, etc., that is used.

The tables and figures presented in this chapter are listed below:

Fundamental constants	Table C-1
Atomic weights	Table C-2
Length equivalents	Table C-3
Volume equivalents	Table C-4
Weight equivalents	Table C-5
Temperature conversion	Tables C-6 to C-8
Energy equivalents	Table C-9
Specific heat, entropy	Table C-10
Pressure equivalents	Table C-11, Fig. C-1
Viscosities	Tables C-12, C-13, Fig. C-2
Thermal conductivity	Table C-14
Density and specific gravities	Tables C-15, C-16
Mole and weight fractions	Fig. C-3

TABLE C-1.—FUNDAMENTAL CONSTANTS

Perfect gas-law constant, R[*]	1.987 Btu/(lb mole)(°R) 1,543 ft-lb/(lb mole)(°R)
Faraday constant	96,500 int. coulombs/g equivalent 12,160 amp-hr/lb equivalent
Mechanical equivalent of heat,[†] *J*	778.1 ft-lb/Btu
Standard atmosphere[‡]	14.696 psi
Temperature of melting ice	491.7°R
Acceleration due to gravity, *g*:	
Standard value	32.17 ft/(sec)^2
0° latitude	32.09
20° latitude	32.11
40° latitude	32.16
60° latitude	32.22
80° latitude	32.25

(Correction for altitude = −0.003 ft/(sec)^2 for each 1,000 ft above sea level)

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[*] See Table E-1.

[†] See Table C-9.

[‡] See Fig. C-1.

TABLE C-2.—ATOMIC WEIGHTS OF ELEMENTS
(Values adopted by the International Committee on Atomic Weights, 1942)

Name	Symbol	Atomic weight	Name	Symbol	Atomic weight
Aluminum	Al	26.97	Molybdenum	Mo	95.95
Antimony	Sb	121.76	Neodymium	Nd	144.27
Argon	A	39.944	Neon	Ne	20.183
Arsenic	As	74.91	Nickel	Ni	58.69
Barium	Ba	137.36	Nitrogen	N	14.008
Beryllium	Be	9.02	Osmium	Os	190.2
Bismuth	Bi	209.00	Oxygen	O	16.000
Boron	B	10.82	Palladium	Pd	106.7
Bromine	Br	79.916	Phosphorus	P	30.98
Cadmium	Cd	112.41	Platinum	Pt	195.23
Calcium	Ca	40.08	Potassium	K	39.096
Carbon	C	12.01	Praseodymium	Pr	140.92
Cerium	Ce	140.13	Protoactinium	Pa	231
Cesium	Cs	132.91	Radium	Ra	226.05
Chlorine	Cl	35.457	Radon (niton)	Rn	222
Chromium	Cr	52.01	Rhenium	Re	186.31
Cobalt	Co	58.94	Rhodium	Rh	102.91
Columbium	Cb	92.91	Rubidium	Rb	85.48
Copper	Cu	63.57	Ruthenium	Ru	101.7
Dysprosium	Dy	162.46	Samarium	Sm	150.43
Erbium	Er	167.2	Scandium	Sc	45.10
Europium	Eu	152.0	Selenium	Se	78.96
Fluorine	F	19.000	Silicon	Si	28.06
Gadolinium	Gd	156.9	Silver	Ag	107.880
Gallium	Ga	69.72	Sodium	Na	22.997
Germanium	Ge	72.60	Strontium	Sr	87.63
Gold	Au	197.2	Sulphur	S	32.06
Hafnium	Hf	178.6	Tantalum	Ta	180.88
Helium	He	4.003	Tellurium	Te	127.61
Holmium	Ho	164.94	Terbium	Tb	159.2
Hydrogen	H	1.0080	Thallium	Tl	204.39
Indium	In	114.76	Thorium	Th	232.12
Iodine	I	126.92	Thulium	Tm	169.4
Iridium	Ir	193.1	Tin	Sn	118.70
Iron	Fe	55.85	Titanium	Ti	47.90
Krypton	Kr	83.7	Tungsten	W	183.92
Lanthanum	La	138.92	Uranium	U	238.07
Lead	Pb	207.21	Vanadium	V	50.95
Lithium	Li	6.940	Xenon	Xe	131.3
Lutecium	Lu	174.99	Ytterbium	Yb	173.04
Magnesium	Mg	24.32	Yttrium	Y	88.92
Manganese	Mn	54.93	Zinc	Zn	65.38
Mercury	Hg	200.61	Zirconium	Zr	91.22

TABLE C-3.—LENGTH EQUIVALENTS

Inches	Feet	Yards	Meters
1	0.08333	0.02778	0.0254
12	1	0.3333	0.3048
36	3	1	0.9144
39.37	3.281	1.0936	1

1 chain = 66 ft 1 mile = 5,280 ft 1 rod = 16.5 ft
1 nautical mile = 6,080.2 ft 1 fathom = 6 ft

Example: 1 m = 39.37 in.

TABLE C-4.—VOLUME EQUIVALENTS

Cu in.	Cu ft	U.S. apothecary oz	U.S. gal	Liters
1,000	0.5787	554	4.329	16.39
1,728	1	957.5	7.481	28.32
1,805	1.044	1,000	7.813	29.57
231	0.1337	128	1	3.785
61.02	0.03531	33.81	0.2642	1

1 gal = 4 qt = 8 pt
1 petroleum bbl = 42 gal
1 l = 1,000.027 cc
1 imperial gal = 1.2 U.S. gal

Example: 1 oz $= \frac{1{,}805}{1{,}000} = 1.805$ cu in.

TABLE C-5.—WEIGHT EQUIVALENTS

1 lb avoirdupois = 16 oz (avdp) = 453.6 g = 7,000 grains
1 short ton = 2,000 lb = 0.9072 metric ton
1 long ton = 2,240 lb = 1.016 metric tons
1 metric ton = 2,205 lb = 1,000 kg
1 lb troy or apothecary = 12 oz troy or apothecary
= 0.8229 lb avoirdupois
= 373.2 g

TABLE C-6.—CONVERSION TABLE: DEGREES CENTIGRADE TO DEGREES FAHRENHEIT

°F = 1.8 × °C + 32

°C	0	10	20	30	40	50	60	70	80	90
	F	F	F	F	F	F	F	F	F	F
−200	−328	−346	−364	−382	−400	−418	−436	−454	......	......
−100	−148	−166	−184	−202	−220	−238	−256	−274	−292	−310
−0	+32	+14	−4	−22	−40	−58	−76	−94	−112	−130
0	32	50	68	86	104	122	140	158	176	194
100	212	230	248	266	284	302	320	338	356	374
200	392	410	428	446	464	482	500	518	536	554
300	572	590	608	626	644	662	680	698	716	734
400	752	770	788	806	824	842	860	878	896	914
500	932	950	968	986	1004	1022	1040	1058	1076	1094
600	1112	1130	1148	1166	1184	1202	1220	1238	1256	1274
700	1292	1310	1328	1346	1364	1382	1400	1418	1436	1454
800	1472	1490	1508	1526	1544	1562	1580	1598	1616	1634
900	1652	1670	1688	1706	1724	1742	1760	1778	1796	1814
1000	1832	1850	1868	1886	1904	1922	1940	1958	1976	1994
1100	2012	2030	2048	2066	2084	2102	2120	2138	2156	2174
1200	2192	2210	2228	2246	2264	2282	2300	2318	2336	2354
1300	2372	2390	2408	2426	2444	2462	2480	2498	2516	2534
1400	2552	2570	2588	2606	2624	2642	2660	2678	2696	2714
1500	2732	2750	2768	2786	2804	2822	2840	2858	2876	2894
1600	2912	2930	2948	2966	2984	3002	3020	3038	3056	3074
1700	3092	3110	3128	3146	3164	3182	3200	3218	3236	3254
1800	3272	3290	3308	3326	3344	3362	3380	3398	3416	3434
1900	3452	3470	3488	3506	3524	3542	3560	3578	3596	3614
2000	3632	3650	3668	3686	3704	3722	3740	3758	3776	3794
2100	3812	3830	3848	3866	3884	3902	3920	3938	3956	3974
2200	3992	4010	4028	4046	4064	4082	4100	4118	4136	4154
2300	4172	4190	4208	4226	4244	4262	4280	4298	4316	4334
2400	4352	4370	4388	4406	4424	4442	4460	4478	4496	4514
2500	4532	4550	4568	4586	4604	4622	4640	4658	4676	4694
2600	4712	4730	4748	4766	4784	4802	4820	4838	4856	4874
2700	4892	4910	4928	4946	4964	4982	5000	5018	5036	5054
2800	5072	5090	5108	5126	5144	5162	5180	5198	5216	5234
2900	5252	5270	5288	5306	5324	5342	5360	5378	5396	5414
3000	5432	5450	5468	5486	5504	5522	5540	5558	5576	5594
3100	5612	5630	5648	5666	5684	5702	5720	5738	5756	5774
3200	5792	5810	5828	5846	5864	5882	5900	5918	5936	5954
3300	5972	5990	6008	6026	6044	6062	6080	6098	6116	6134
3400	6152	6170	6188	6206	6224	6242	6260	6278	6296	6314
3500	6332	6350	6368	6386	6404	6422	6440	6458	6476	6494
3600	6512	6530	6548	6566	6584	6602	6620	6638	6656	6674
3700	6692	6710	6728	6746	6764	6782	6800	6818	6836	6854
3800	6872	6890	6908	6926	6944	6962	6980	6998	7016	7034
3900	7052	7070	7088	7106	7124	7142	7160	7178	7196	7214
°C	0	10	20	30	40	50	60	70	80	90

°C	°F
1	1.8
2	3.6
3	5.4
4	7.2
5	9.0
6	10.8
7	12.6
8	14.4
9	16.2
10	18.0

°F	°C
1	0.56
2	1.11
3	1.67
4	2.22
5	2.78
6	3.33
7	3.89
8	4.44
9	5.00
10	5.56
11	6.11
12	6.67
13	7.22
14	7 78
15	8.33
16	8.89
17	9.44
18	10.00

Examples: 1347°C = 2444°F + 12.6°F = 2456.6°F
3367°F = 1850°C + 2.78°C = 1852.78°C

TABLE C-7.—CONVERSION TABLE: DEGREES FAHRENHEIT TO DEGREES CENTIGRADE

$$°C = \frac{°F - 32}{1.8}$$

°F	0	10	20	30	40	50	60	70	80	90
	C	C	C	C	C	C	C	C	C	C
−400	−240.0	−245.5	−251.1	−256.6	−262.2	−267.7	....	....	....	....
−300	−184.4	−190.0	−195.5	−201.1	−206.6	−212.2	−217.7	−223.3	−228.8	−234.4
−200	−128.8	−134.4	−140.0	−145.5	−151.1	−156.6	−162.2	−167.7	−173.3	−178.8
−100	−73.3	−78.8	−84.4	−90.0	−95.5	−101.1	−106.6	−112.2	−117.7	−123.3
−0	−17.7	−23.3	−28.8	−34.4	−40.0	−45.5	−51.1	−56.6	−62.2	−67.7
0	−17.7	−12.2	−6.6	−1.1	+4.4	+10.0	+15.5	+21.1	+26.6	+32.2
100	37.7	43.3	48.8	54.4	60.0	65.5	71.1	76.6	82.2	87.7
200	93.3	98.8	104.4	110.0	115.5	121.1	126.6	132.2	137.7	143.3
300	148.8	154.4	160.0	165.5	171.1	176.6	182.2	187.7	193.3	198.8
400	204.4	210.0	215.5	221.1	226.6	232.2	237.7	243.3	248.8	254.4
500	260.0	265.5	271.1	276.6	282.2	287.7	293.3	298.8	304.4	310.0
600	315.5	321.1	326.6	332.2	337.7	343.3	348.8	354.4	360.0	365.5
700	371.1	376.6	382.2	387.7	393.3	398.8	404.4	410.0	415.5	421.1
800	426.6	432.2	437.7	443.3	448.8	454.4	460.0	465.5	471.1	476.6
900	482.2	487.7	493.3	498.8	504.4	510.0	515.5	521.1	526.6	532.2
1000	537.7	543.3	548.8	554.4	560.0	565.5	571.1	576.6	582.2	587.7
1100	593.3	598.8	604.4	610.0	615.5	621.1	626.6	632.2	637.7	643.3
1200	648.8	654.4	660.0	665.5	671.1	676.6	682.2	687.7	693.3	698.8
1300	704.4	710.0	715.5	721.1	726.6	732.2	737.7	743.3	748.8	754.4
1400	760.0	765.5	771.1	776.6	782.2	787.7	793.3	798.8	804.4	810.0
1500	815.5	821.1	826.6	832.2	837.7	843.3	848.8	854.4	860.0	865.5
1600	871.1	876.6	882.2	887.7	893.3	898.8	904.4	910.0	915.5	921.1
1700	926.6	932.2	937.7	943.3	948.8	954.4	960.0	965.5	971.1	976.6
1800	982.2	987.7	993.3	998.8	1004.4	1010.0	1015.5	1021.1	1026.6	1032.2
1900	1037.7	1043.3	1048.8	1054.4	1060.0	1065.5	1071.1	1076.6	1082.2	1087.7
2000	1093.3	1098.8	1104.4	1110.0	1115.5	1121.1	1126.6	1132.2	1137.7	1143.3
2100	1148.8	1154.4	1160.0	1165.5	1171.1	1176.6	1182.2	1187.7	1193.3	1198.8
2200	1204.4	1210.0	1215.5	1221.1	1226.6	1232.2	1237.7	1243.3	1248.8	1254.4
2300	1260.0	1265.5	1271.1	1276.6	1282.2	1287.7	1293.3	1298.8	1304.4	1310.0
2400	1315.5	1321.1	1326.6	1332.2	1337.7	1343.3	1348.8	1354.4	1360.0	1365.5
2500	1371.1	1376.6	1382.2	1387.7	1393.3	1398.8	1404.4	1410.0	1415.5	1421.1
2600	1426.6	1432.2	1437.7	1443.3	1448.8	1454.4	1460.0	1465.5	1471.1	1476.6
2700	1482.2	1487.7	1493.3	1498.8	1504.4	1510.0	1515.5	1521.1	1526.6	1532.2
2800	1537.7	1543.3	1548.8	1554.4	1560.0	1565.5	1571.1	1576.6	1582.2	1587.7
2900	1593.3	1598.8	1604.4	1610.0	1615.5	1621.1	1626.6	1632.2	1637.7	1643.3
3000	1648.8	1654.4	1660.0	1665.5	1671.1	1676.6	1682.2	1687.7	1693.3	1698.8
3100	1704.4	1710.0	1715.5	1721.1	1726.6	1732.2	1737.7	1743.3	1748.8	1754.4
3200	1760.0	1765.5	1771.1	1776.6	1782.2	1787.7	1793.3	1798.8	1804.4	1810.0
3300	1815.5	1821.1	1826.6	1832.2	1837.7	1843.3	1848.8	1854.4	1860.0	1865.5
3400	1871.1	1876.6	1882.2	1887.7	1893.3	1898.8	1904.4	1910.0	1915.5	1921.1
3500	1926.6	1932.2	1937.7	1943.3	1948.8	1954.4	1960.0	1965.5	1971.1	1976.6
3600	1982.2	1987.7	1993.3	1998.8	2004.4	2010.0	2015.5	2021.1	2026.6	2032.2
°F	0	10	20	30	40	50	60	70	80	90

°F	°C
1	0.5
2	1.1
3	1.6
4	2.2
5	2.7
6	3.3
7	3.8
8	4.4
9	5.0

Examples: −246.0°F = −151.11°C − 3.33°C = −154.44°C

2423.5°F = 1326.66°C + 1.66°C + 0.27°C = 1328.61°C

TABLE C-8.—CONVERSION OF DEGREES KELVIN TO DEGREES RANKINE AND DEGREES FAHRENHEIT

°R = 1.8 × °K = 459.7 + °F

Kelvin, °K	Rankine, °R	Fahrenheit, °F
100	180	−280
150	270	−190
200	360	−100
250	450	−10
273.16	491.7	32
298.16	536.7	77
300	540	80
350	630	170
373.16	671.7	212
400	720	260
450	810	350
500	900	440
550	990	530
600	1080	620
650	1170	710
700	1260	800
750	1350	890
800	1440	980
900	1620	1160
1000	1800	1340
1100	1980	1520
1200	2160	1700
1250	2250	1790
1300	2340	1880
1400	2520	2060
1500	2700	2240
1600	2880	2420
1700	3060	2600
1750	3150	2690
1800	3240	2780
1900	3420	2960
2000	3600	3140
2100	3780	3320
2200	3960	3500
2250	4050	3590
2300	4140	3680
2400	4320	3860
2500	4500	4040
2750	4950	4490
3000	5400	4940

NOTE: Fahrenheit temperatures given are rounded to nearest degree.

TABLE C-9.—ENERGY EQUIVALENTS

Ft-lb	Hp-hr	Kw-hr	Kg-meters	Joules (10^7 ergs)	Btu	Kg-cal
1,000,000	0.5051	0.3766	138,300	1,356,000	1286	324.1
1,980,000	*1*	0.7457	273,750	2,684,500	2544	641.7
2,655,000	1.341	*1*	367,100	3,600,000	3415	860.0
723,300	0.3653	0.2724	*100,000*	980,600	929.6	234.4
737,600	0.3725	0.2778	101,970	*1,000,000*	948.6	239
778,100	0.3930	0.2928	107,500	1,054,000	*1000*	252
308,600	0.1558	0.1162	42,690	418,300	396.8	*100*

1 watt = 1 joule/sec = 0.7376 ft-lb/sec
1 metric hp = 0.9863 hp
1 therm = 100,000 Btu

Example: $1\text{ joule} = \dfrac{737{,}600}{1{,}000{,}000} = 0.7376\text{ ft-lb}$

TABLE C-10.—SPECIFIC HEAT AND ENTROPY EQUIVALENTS

Units of		Equivalents	
Specific heat	Entropy		
Btu/(lb)(°F)	Btu/(lb)(°R)	1	0.2390
Cal/(g)(°C)	Cal/(g)(°K)	1	0.2390
Joule/(g)(°C)	Joule/(g)(°K)	4.183	1

TABLE C-11.—PRESSURE EQUIVALENTS

Atm.	Psi	Kg/sq cm	Megabars	Columns of mercury at 32°F		Columns of water at 60°F	
				M	In.	In.	Ft
1	14.70	1.033	1.013	0.760	29.92	407.2	33.93
0.0680	1	0.0703	0.06895	0.05171	2.036	27.70	2.309
0.968	14.22	1	0.9807	0.7355	28.96	394	32.84
0.987	14.50	1.020	1	0.750	29.53	402	33.48
1.316	19.34	1.360	1.333	1	39.37	536	44.64
0.03342	0.4912	0.03453	0.03386	0.0254	1	13.61	1.134
0.00246	0.0361	0.00254	0.00249	0.00187	0.0735	1	0.0833
0.0295	0.4332	0.0304	0.0299	0.0224	0.8819	12	1

1 psi = 144 psf = 2304 oz/sq ft

Example: 1 kg/sq cm = 0.968 atm

NOTE: Absolute pressure = gauge pressure + atmospheric pressure (see Fig. C-1).

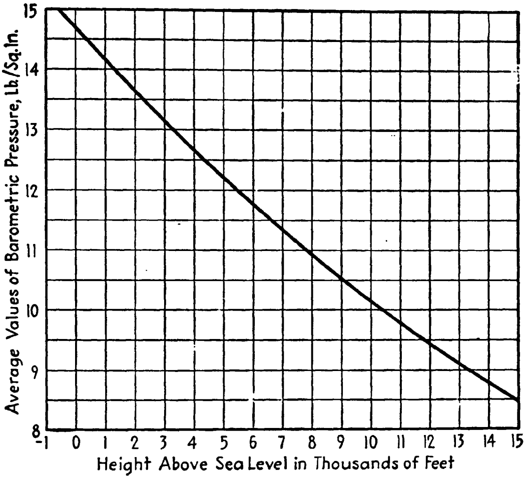


FIG. C-1.—Barometric pressures at different altitudes.

TABLE C-12.—VISCOSITY EQUIVALENTS

Poises $= \frac{\text{dyne-sec}}{\text{sq cm}}$	$\frac{\text{Kg-sec}}{\text{sq m}}$	$\frac{\text{Lb}}{\text{ft-sec}}$	$\frac{\text{Lb-sec}}{\text{sq ft}}$
1	0.0102	0.0672	0.00209
98	1	6.59	0.205
14.88	0.152	1	0.0311
4.78	4.88	32.2	1

1 lb/ft-sec = 3,600 lb/ft-hr   1 lb-hr/sq ft = 3,600 lb-sec/sq ft

1 poise = 100 centipoises = 0.1 kg/m-sec

Examples: 1 centipoise $= \frac{1}{100}$ poise $= \frac{0.0672}{100}$, or 0.000672 lb/ft-sec

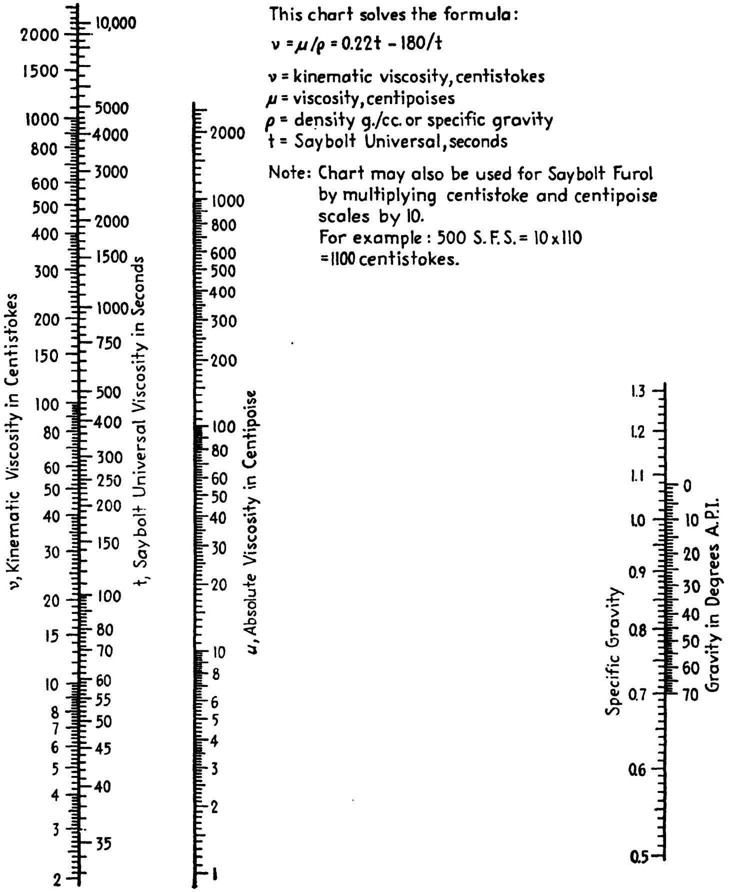
1 lb/ft-hr $= \frac{1}{3{,}600}$ lb/ft-sec $= \frac{14.88}{3{,}600}$, or 0.00413 poise

TABLE C-13.—KINEMATIC VISCOSITY SCALES

Scale	Equation (approx)
Saybolt Universal*	$\nu = \frac{\mu}{\rho} = 0.22t - \frac{180}{t}$
Saybolt Furol*	$\nu = \frac{\mu}{\rho} = 2.2t - \frac{1{,}800}{t}$
Redwood	$\nu = \frac{\mu}{\rho} = 0.26t - \frac{171.5}{t}$
Redwood Admiralty	$\nu = \frac{\mu}{\rho} = 0.27t - \frac{2{,}000}{t}$
Engler	$\nu = \frac{\mu}{\rho} = 0.147t - \frac{374}{t}$

NOTE:
ν = kinematic viscosity, centistokes
μ = viscosity, centipoises
ρ = density, g/cc
t = time of standard flow, sec.

* See Fig. C-2.



This chart solves the formula:

$\nu = \mu/\rho = 0.22t - 180/t$

ν = kinematic viscosity, centistokes
μ = viscosity, centipoises
ρ = density g./cc. or specific gravity
t = Saybolt Universal, seconds

Note: Chart may also be used for Saybolt Furol by multiplying centistoke and centipoise scales by 10.
For example: 500 S.F.S. = 10 x 110 = 1100 centistokes.

FIG. C-2.—Viscosity conversion chart. (*Reproduced by permission of Product Engineering.*)

TABLE C-14.—THERMAL CONDUCTIVITY EQUIVALENTS

Btu / (hr)(sq ft)(°F/ft)	Btu / (hr)(sq ft)(°F/in.)	Cal / (sec)(sq cm)(°C/cm)	Watts / (sq cm)(°C/cm)
1	12	0.004134	0.01728
0.0833	1	0.0003445	0.001440
241.9	2903	1	4.183
57.83	694.0	0.2391	1

Example: 1 watt/(sq cm) (°C/cm) = 57.83 Btu/(hr)(sq ft)(°F/ft).

TABLE C-15.—DENSITY EQUIVALENTS

$\frac{\text{G}}{\text{cu cm}}$	$\frac{\text{Lb}}{\text{cu in.}}$	$\frac{\text{Lb}}{\text{cu ft}}$	$\frac{\text{Short tons}}{\text{cu yd}}$	$\frac{\text{Lb}}{\text{U.S. gal}}$
1	0.03613	62.43	0.8428	8.345
27.68	1	1,728	23.33	231
1.602	0.05787	100	1.350	13.37
1.186	0.04286	74.07	1	9.902
1.198	0.04329	74.81	1.010	10

Example: 1 lb/gal $= \frac{74.81}{10} =$ 7.481 lb/cu ft.

Examples: (1) Given $M_B/M_A = 4.3$ and $w_A = 0.41$, then $x_A = 0.75$
(2) Given $M_B/M_A = 8.6$ and $w_A = 0.91$, then $x_A = 0.988$ (high scales)
(3) Given $M_B/M_A = 1.95$ and $x_A = 0.44$, then $w_A = 0.29$

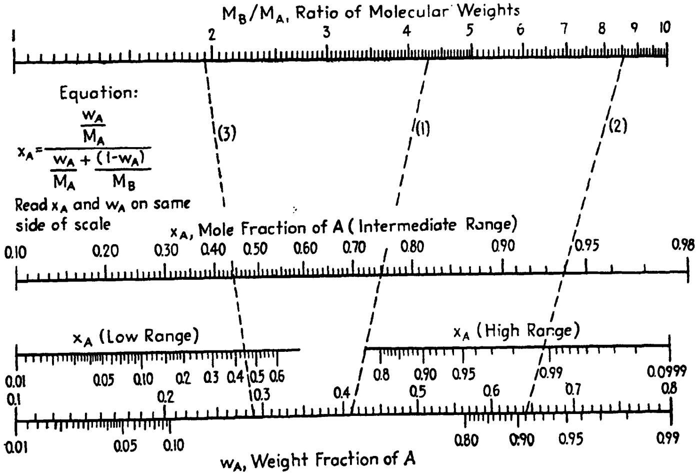


FIG. C-3.—Conversion of weight fractions to mole fractions. (*Bridger, Chem. and Met. Eng., August,* 1937.)

TABLE C-16.—CONVERSION TABLE: SPECIFIC GRAVITY TO DEGREES BAUMÉ, DEGREES AMERICAN PETROLEUM INSTITUTE, DEGREES TWADDELL, POUNDS PER GALLON, AND POUNDS PER CUBIC FOOT

Specific gravity at 60°F relative to water at 60°F

$$= \text{sp gr }(60/60) = 62.4\text{ lb/cu ft} = 8.34\text{ lb/U.S. gal}$$

$$\text{Degrees Baumé} = {}^{\circ}\text{Bé} = 145 - \frac{145}{\text{sp gr}}\text{ (heavier than water)}$$

$$= \frac{140}{\text{sp gr}} - 130\text{ (lighter than water)}$$

$$\text{Degrees American Petroleum Institute} = {}^{\circ}\text{API} = \frac{141.5}{\text{sp gr}} - 131.5$$

$$\text{Degrees Twaddell} = {}^{\circ}\text{Tw} = 200 \times (\text{sp gr} - 1)$$

(Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York, 1941)

Sp gr	°Bé	°A.P.I.	Lb/gal	Lb/cu ft
0.600	103.33	104.33	5.0025	37.4219
0.605	101.41	102.38	5.0442	37.7338
0.610	99.51	100.47	5.0858	38.0456
0.615	97.64	98.58	5.1275	38.3575
0.620	95.80	96.73	5.1692	38.6693
0.625	94.00	94.90	5.2109	38.9812
0.630	92.22	93.10	5.2526	39.2930
0.635	90.47	91.33	5.2943	39.6049
0.640	88.75	89.59	5.3360	39.9167
0.645	87.05	87.88	5.3776	40.2286
0.650	85.38	86.19	5.4193	40.5404
0.655	83.74	84.53	5.4610	40.8523
0.660	82.12	82.89	5.5027	41.1641
0.665	80.53	81.28	5.5444	41.4760
0.670	78.95	79.69	5.5861	41.7878
0.675	77.41	78.13	5.6278	42.0997
0.680	75.88	76.59	5.6695	42.4115
0.685	74.38	75.07	5.7111	42.7234
0.690	72.90	73.57	5.7528	43.0352
0.695	71.44	72.10	5.7945	43.3471
0.700	70.00	70.64	5.8362	43.6589
0.705	68.58	69.21	5.8779	43.9708
0.710	67.18	67.80	5.9196	44.2826
0.715	65.80	66.40	5.9613	44.5945
0.720	64.44	65.03	6.0030	44.9063
0.725	63.10	63.67	6.0446	45.2182
0.730	61.78	62.34	6.0863	45.5300
0.735	60.48	61.02	6.1280	45.8419
0.740	59.19	59.72	6.1697	46.1537
0.745	57.92	58.43	6.2114	46.4656
0.750	56.67	57.17	6.2531	46.7774
0.755	55.43	55.92	6.2948	47.0893
0.760	54.21	54.68	6.3365	47.4011
0.765	53.01	53.47	6.3781	47.7130
0.770	51.81	52.27	6.4198	48.0248
0.775	50.65	51.08	6.4615	48.3367
0.780	49.49	49.91	6.5032	48.6485
0.785	48.34	48.75	6.5449	48.9604
0.790	47.22	47.61	6.5866	49.2722
0.795	46.10	46.49	6.6283	49.5841
0.800	45.00	45.38	6.6700	49.8959
0.805	43.91	44.28	6.7116	50.2077
0.810	42.84	43.19	6.7533	50.5196
0.815	41.78	42.12	6.7950	50.8315
0.820	40.73	41.06	6.8367	51.1433
0.825	39.70	40.02	6.8784	51.4552
0.830	38.67	38.98	6.9201	51.7670
0.835	37.66	37.96	6.9618	52.0789
0.840	36.67	36.95	7.0034	52.3907
0.845	35.68	35.96	7.0451	52.7026
0.850	34.71	34.97	7.0868	53.0144
0.855	33.74	34.00	7.1285	53.3263
0.860	32.79	33.03	7.1702	53.6381
0.865	31.85	32.08	7.2119	53.9500
0.870	30.92	31.14	7.2536	54.2618
0.875	30.00	30.21	7.2953	54.5737
0.880	29.09	29.30	7.3369	54.8855
0.885	28.19	28.39	7.3786	55.1974
0.890	27.30	27.49	7.4203	55.5092
0.895	26.42	26.60	7.4620	55.8211
0.900	25.56	25.72	7.5037	56.1329
0.905	24.70	24.85	7.5454	56.4448
0.910	23.85	23.99	7.5871	56.7566
0.915	23.01	23.14	7.6288	57.0685
0.920	22.17	22.30	7.6704	57.3803
0.925	21.35	21.47	7.7121	57.6922
0.930	20.54	20.65	7.7538	58.0040
0.935	19.73	19.84	7.7955	58.3159
0.940	18.93	19.03	7.8372	58.6277
0.945	18.15	18.24	7.8789	58.9396
0.950	17.37	17.45	7.9206	59.2514
0.955	16.60	16.67	7.9623	59.5633
0.960	15.83	15.90	8.0039	59.8751
0.965	15.08	15.13	8.0456	60.1878
0.970	14.33	14.38	8.0873	60.4980
0.975	13.59	13.63	8.1290	60.8107
0.980	12.86	12.89	8.1707	61.1225
0.985	12.13	12.15	8.2124	61.4344
0.990	11.41	11.43	8.2541	61.7462
0.995	10.70	10.71	8.2958	62.0581
1.000	10.00	10.00	8.3374	62.3699

TABLE C-16.—CONVERSION TABLE: SPECIFIC GRAVITY TO DEGREES BAUMÉ, DEGREES AMERICAN PETROLEUM INSTITUTE, DEGREES TWADDELL, POUNDS PER GALLON, AND POUNDS PER CUBIC FOOT (*Continued*)

Sp gr	°Bé	°Tw	Lb/gal	Lb/cu ft	Sp gr	°Bé	°Tw	Lb/gal	Lb/cu ft
1.005	0.72	1	8.3791	62.6817	1.255	29.46	51	10.4635	78.2742
1.010	1.44	2	8.4208	62.9936	1.260	29.92	52	10.5052	78.5861
1.015	2.14	3	8.4625	63.3054	1.265	30.38	53	10.5469	78.8979
1.020	2.84	4	8.5042	63.6173	1.270	30.83	54	10.5885	79.2098
1.025	3.54	5	8.5459	63.9291	1.275	31.27	55	10.6302	79.5216
1.030	4.22	6	8.5876	64.2410	1.280	31.72	56	10.6719	79.8335
1.035	4.90	7	8.6293	64.5528	1.285	32.16	57	10.7136	80.1453
1.040	5.58	8	8.6709	64.8647	1.290	32.60	58	10.7553	80.4572
1.045	6.24	9	8.7126	65.1765	1.295	33.03	59	10.7970	80.7690
1.050	6.91	10	8.7543	65.4884	1.300	33.46	60	10.8387	81.0809
1.055	7.56	11	8.7960	65.8002	1.305	33.89	61	10.8804	81.3927
1.060	8.21	12	8.8377	66.1121	1.310	34.31	62	10.9220	81.7046
1.065	8.85	13	8.8794	66.4239	1.315	34.73	63	10.9637	82.0164
1.070	9.49	14	8.9211	66.7358	1.320	35.15	64	11.0054	82.3283
1.075	10.12	15	8.9627	67.0476	1.325	35.57	65	11.0471	82.6401
1.080	10.74	16	9.0044	67.3595	1.330	35.98	66	11.0888	82.9520
1.085	11.36	17	9.0461	67.6713	1.335	36.39	67	11.1305	83.2638
1.090	11.97	18	9.0878	67.9832	1.340	36.79	68	11.1722	83.5757
1.095	12.58	19	9.1295	68.2950	1.345	37.19	69	11.2139	83.8875
1.100	13.18	20	9.1712	68.6069	1.350	37.59	70	11.2555	84.1994
1.105	13.78	21	9.2129	68.9187	1.355	37.99	71	11.2972	84.5112
1.110	14.37	22	9.2546	69.2306	1.360	38.38	72	11.3389	84.8231
1.115	14.96	23	9.2962	69.5424	1.365	38.77	73	11.3806	85.1349
1.120	15.54	24	9.3380	69.8543	1.370	39.16	74	11.4223	85.4468
1.125	16.11	25	9.3796	70.1661	1.375	39.55	75	11.4640	85.7586
1.130	16.68	26	9.4213	70.4780	1.380	39.93	76	11.5057	86.0705
1.135	17.25	27	9.4630	70.7898	1.385	40.31	77	11.5474	86.3823
1.140	17.81	28	9.5047	71.1017	1.390	40.68	78	11.5890	86.6942
1.145	18.36	29	9.5464	71.4135	1.395	41.06	79	11.6307	87.0060
1.150	18.91	30	9.5881	71.7254	1.400	41.43	80	11.6724	87.3179
1.155	19.46	31	9.6297	72.0372	1.405	41.80	81	11.7141	87.6297
1.160	20.00	32	9.6714	72.3491	1.410	42.17	82	11.7558	87.9416
1.165	20.54	33	9.7131	72.6609	1.415	42.53	83	11.7975	88.2534
1.170	21.07	34	9.7548	72.9728	1.420	42.89	84	11.8392	88.5653
1.175	21.60	35	9.7965	73.2846	1.425	43.25	85	11.8809	88.8771
1.180	22.12	36	9.8382	73.5965	1.430	43.60	86	11.9225	89.1890
1.185	22.64	37	9.8799	73.9083	1.435	43.95	87	11.9642	89.5008
1.190	23.15	38	9.9216	74.2202	1.440	44.31	88	12.0059	89.8127
1.195	23.66	39	9.9632	74.5320	1.445	44.65	89	12.0476	90.1245
1.200	24.17	40	10.0049	74.8439	1.450	45.00	90	12.0893	90.4364
1.205	24.67	41	10.0466	75.1557	1.455	45.34	91	12.1310	90.7482
1.210	25.16	42	10.0883	75.4676	1.460	45.68	92	12.1727	91.0600
1.215	25.66	43	10.1300	75.7794	1.465	46.02	93	12.2143	91.3719
1.220	26.15	44	10.1717	76.0913	1.470	46.36	94	12.2560	91.6838
1.225	26.63	45	10.2134	76.4031	1.475	46.69	95	12.2977	91.9956
1.230	27.11	46	10.2551	76.7149	1.480	47.03	96	12.3394	92.3075
1.235	27.59	47	10.2967	77.0268	1.485	47.36	97	12.3811	92.6193
1.240	28.06	48	10.3384	77.3387	1.490	47.68	98	12.4228	92.9312
1.245	28.53	49	10.3801	77.6505	1.495	48.01	99	12.4645	93.2430
1.250	29.00	50	10.4218	77.9624	1.500	48.33	100	12.5062	93.5549

TABLE C-16.—CONVERSION TABLE: SPECIFIC GRAVITY TO DEGREES BAUMÉ, DEGREES AMERICAN PETROLEUM INSTITUTE, DEGREES TWADDELL, POUNDS PER GALLON, AND POUNDS PER CUBIC FOOT (*Concluded*)

Sp gr	°Bé	°Tw	Lb/gal	Lb/cu ft	Sp gr	°Bé	°Tw	Lb/gal	Lb/cu ft
1.505	48.65	101	12.5478	93.8667	1.755	62.38	151	14.6322	109.4592
1.510	48.97	102	12.5895	94.1785	1.760	62.61	152	14.6739	109.7710
1.515	49.29	103	12.6312	94.4904	1.765	62.85	153	14.7156	110.0829
1.520	49.61	104	12.6729	94.8022	1.770	63.08	154	14.7573	110.3947
1.525	49.92	105	12.7146	95.1141	1.775	63.31	155	14.7990	110.7066
1.530	50.23	106	12.7563	95.4259	1.780	63.54	156	14.8406	111.0184
1.535	50.54	107	12.7980	95.7378	1.785	63.77	157	14.8823	111.3303
1.540	50.84	108	12.8397	96.0496	1.790	64.00	158	14.9240	111.6421
1.545	51.15	109	12.8813	96.3615	1.795	64.22	159	14.9657	111.9540
1.550	51.45	110	12.9230	96.6733	1.800	64.44	160	15.0074	112.2658
1.555	51.75	111	12.9647	96.9852	1.805	64.67	161	15.0491	112.5777
1.560	52.05	112	13.0064	97.2970	1.810	64.89	162	15.0908	112.8895
1.565	52.35	113	13.0481	97.6089	1.815	65.11	163	15.1325	113.2014
1.570	52.64	114	13.0898	97.9207	1.820	65.33	164	15.1741	113.5132
1.575	52.94	115	13.1315	98.2326	1.825	65.55	165	15.2158	113.8251
1.580	53.23	116	13.1732	98.5444	1.830	65.77	166	15.2575	114.1369
1.585	53.52	117	13.2148	98.8563	1.835	65.98	167	15.2992	114.4488
1.590	53.81	118	13.2565	99.1681	1.840	66.20	168	15.3409	114.7606
1.595	54.09	119	13.2982	99.4800	1.845	66.41	169	15.3826	115.0725
1.600	54 38	120	13.3399	99.7918	1.850	66.62	170	15.4243	115.3843
1.605	54.66	121	13.3816	100.1037	1.855	66.83	171	15.4660	115.6962
1.610	54.94	122	13.4233	100.4155	1.860	67.04	172	15.5076	116.0080
1.615	55.22	123	13.4650	100.7274	1.865	67.25	173	15.5493	116.3199
1.620	55.49	124	13.5067	101.0392	1.870	67.46	174	15.5910	116.6317
1.625	55.77	125	13.5483	101.3511	1.875	67.67	175	15.6327	116.9436
1.630	56.04	126	13.5900	101.6629	1.880	67.87	176	15.6744	117.2554
1.635	56.32	127	13.6317	101.9748	1.885	68.08	177	15.7161	117.5673
1.640	56.55	128	13.6734	102 2866	1.890	68.28	178	15.7578	117.8791
1.645	56.85	129	13.7151	102.5985	1.895	68.48	179	15.7994	118.1910
1.650	57.12	130	13.7568	102.9103	1.900	68.68	180	15.8411	118.5028
1.655	57.39	131	13.7985	103.2222	1.905	68.88	181	15.8828	118.8147
1.660	57.65	132	13.8402	103.5340	1.910	69.08	182	15.9245	119.1265
1.665	57.91	133	13.8818	103.8459	1.915	69.28	183	15.9662	119.4384
1.670	58.17	134	13.9235	104.1578	1.920	69.48	184	16.0079	119.7502
1.675	58.43	135	13.9652	104.4696	1.925	69.68	185	16.0496	120.0621
1.680	58.69	136	14.0069	104.7814	1.930	69.87	186	16.0913	120.3739
1.685	58.95	137	14.0486	105.0933	1.935	70.06	187	16.1329	120.6858
1.690	59.20	138	14.0903	105.4051	1.940	70.26	188	16.1746	120.9976
1.695	59.45	139	14.1320	105.7170	1.945	70.45	189	16.2163	121.3095
1.700	59.71	140	14.1736	106.0287	1.950	70.64	190	16.2580	121.6213
1.705	59.96	141	14.2153	106.3407	1.955	70.83	191	16.2997	121.9332
1.710	60.20	142	14.2570	106.6525	1.960	71.02	192	16.3414	122.2450
1.715	60.45	143	14.2987	106.9644	1.965	71.21	193	16.3831	122.5569
1.720	60.70	144	14.3404	107.2762	1.970	71.40	194	16.4248	122.8687
1.725	60.94	145	14.3821	107.5881	1.975	71.58	195	16.4664	123.1806
1.730	61.18	146	14.4238	107.8999	1.980	71.77	196	16.5081	123.4924
1.735	61.43	147	14.4655	108.2118	1.985	71.95	197	16.5498	123.8043
1.740	61.67	148	14.5071	108.5236	1.990	72.14	198	16.5915	124.1161
1.745	61.91	149	14.5488	108.8355	1.995	72.32	199	16.6332	124.4280
1.750	62.15	150	14.5905	109.1473	2.000	72.50	200	16.6749	124.7398

CHAPTER D

PHYSICAL AND MECHANICAL PROPERTIES

The start of all engineering work rests on a knowledge of the properties of the materials used. Consequently, various properties are discussed in almost every chapter of this book. This chapter gives liquid densities and references to physical data presented in other chapters; a few mechanical properties of selected construction materials; and finally, a brief treatment of corrosion. Because of the extensive amount of information an engineer is likely to require, no one source book can be entirely adequate. Below are listed a number of useful compilations and reference books.

"International Critical Tables," McGraw-Hill Book Company, Inc., New York.

Hodgman, "Handbook of Chemistry and Physics," published annually by the Chemical Rubber Publishing Co., Cleveland, Ohio.

Lange, "Handbook of Chemistry," 5th ed., Handbook Publishers, Sandusky, Ohio, 1944.

Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York, 1941.

Marks, "Mechanical Engineers' Handbook," 4th ed., McGraw-Hill Book Company, Inc., New York, 1941.

Seidell, "Solubilities of Inorganic and Metal Organic Compounds," 3d ed., 1940; and "Solubilities of Organic Compounds," 3d ed., 1941, D. Van Nostrand Company, Inc., New York.

Brady, "Materials Handbook," 5th ed., McGraw-Hill Book Company, Inc., New York, 1944.

"The Metals Handbook," published annually by the American Society of Metals, Cleveland, Ohio.

Warner, "Chemistry of Engineering Materials," 4th ed., McGraw-Hill Book Company, Inc., New York, 1942.

Moore, "Textbook of the Materials of Engineering," 6th ed., McGraw-Hill Book Company, Inc., New York, 1941.

Materials of Construction, *Chem. & Met. Eng.*, September, 1944.

Jeffries and Archer, "The Science of Metals," McGraw-Hill Book Company, Inc., New York, 1924.

Hoyt, "Metals and Alloys Data Book," Reinhold Publishing Corporation, New York, 1943.

Speller, "Corrosion: Causes and Prevention," 2d ed., McGraw-Hill Book Company, Inc., New York, 1935.

Rawdon, "Protective Metallic Coatings," Chemical Catalog Company, Inc., New York, 1928.

Sauveur, "Metallography and Heat Treatment of Iron and Steel," 4th ed., McGraw-Hill Book Company, Inc., New York, 1935.

Norton, "Refractories," 2d ed., McGraw-Hill Book Company, Inc., New York, 1942.

Holtman, "Wood Construction," McGraw-Hill Book Company, Inc., New York, 1929.

Spalding, Hyde, and Robinson, "Masonry Structures," 2d ed., John Wiley & Sons, Inc., New York, 1926.

Taylor and Thompson, "Concrete Plain and Reinforced," 3d ed., John Wiley & Sons, Inc., New York, 1916.

Delmonte, "Plastics in Engineering," Penton Publishing Company, Cleveland, 1939.

Simonds and Bigelow, "The New Plastics," D. Van Nostrand Company, Inc., New York, 1945.

1. Physical Properties of Process Materials

a. Densities of Liquids.—Values are given in chart form for a number of materials. A list of the figures follows:

Density of:	
Light hydrocarbon liquids	Fig. D-1
Typical petroleum products	Fig. D-2
Miscellaneous liquids	Fig. D-3
Heavy liquids	Fig. D-4
Water	Fig. D-5
Ethyl alcohol solutions	Fig. D-6
Sulphuric acid	Fig. D-7
Oleum	Fig. D-8
Nitric acid	Fig. D-9
Hydrochloric acid	Fig. D-10
Phosphoric acid	Fig. D-11
Sodium carbonate solutions (soda ash)	Fig. D-12
Caustic soda solutions	Fig. D-13
Potassium carbonate solution	Fig. D-14
Aqua ammonia	Fig. D-15

Also Fig. E-4 in the next chapter permits the estimation of liquid densities at various temperatures from a single value. Tables E-13 to E-18 give specific volumes of water, carbon dioxide, propane, and ammonia. (The density in pounds per cubic foot is the reciprocal of the specific volume.) Tables H-7 and H-12 give density data on liquid fuels.

Densities of liquid mixtures may, according to the laws of perfect solution, be computed by assuming no volume change on mixing; that is, additive volumes:

$$v = \frac{P_1}{100} v_1 + \frac{P_2}{100} v_2 + \frac{P_3}{100} v_3 + \cdots$$

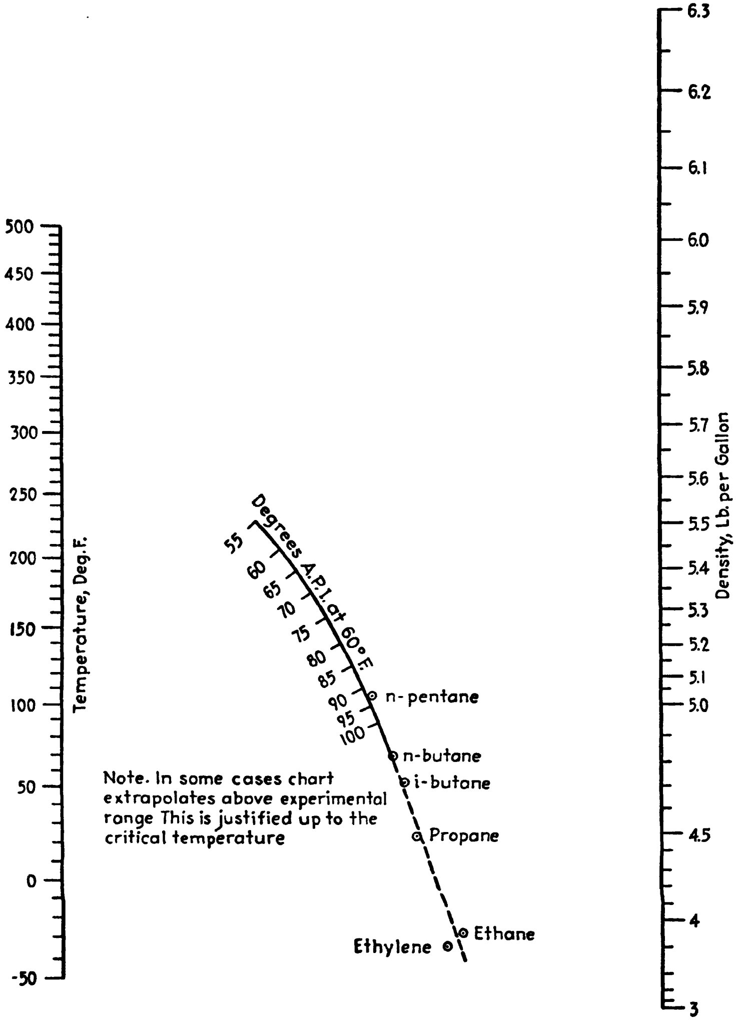
$$\frac{1}{\rho} = \frac{P_1}{100\rho_1} + \frac{P_2}{100\rho_2} + \frac{P_3}{100\rho_3} + \cdots$$

where v = specific volume of mixture
v_1, v_2, v_3 = specific volume of components 1, 2, 3
ρ = density of mixture
ρ_1, ρ_2, ρ_3 = density of components 1, 2, 3
P_1, P_2, P_3 = weight per cent of components 1, 2 3

For hydrocarbon mixtures at moderate pressures this rule works fairly well. Similarly, it is likely to work for mixtures of closely allied liquids. However, many solutions do not follow the rule, which, therefore, should be used with caution, particularly in the case of water solutions.

b. Other Properties.—Data are scattered throughout the book in connection with subjects for which the particular properties are most important. However, as no physical datum is the exclusive property of any one subject, the principal tables and figures are listed in the accompanying tabulation.

Physical property	Tables	Figures
Compressibility factors (reduced equation of state)	....	E-1 to E-3
Liquid density, estimation of	....	E-4
Specific heats:		
Gases	E-3	E-5 to E-9
Solids	E-5, E-11	
Liquids	E-6	E-15
Solutions	E-8 to E-10	
Sensible heats:		
Gases	....	E-10 to E-14
Solids	E-4	
Petroleum liquids	E-7	
Vapor pressures	H-12	E-16 to E-18, H-5
Heats of vaporization	E-12	E-19
Thermodynamic properties:		
Steam	E-13 to E-15	
Propane	E-16	E-20
Ammonia	E-17	E-21
Carbon dioxide	E-18	
Air	M-1	
Heats of formation	E-19, E-20	
Heats of combustion:		
Gases	H-9 to H-11	
Solids	H-2 to H-4	H-1
Liquids	H-7, H-12	H-4
Viscosities:		
Gases	F-2, F-3	F-2 to F-4
Liquids	F-1	F-1, F-4
Heat conductivity	D-2, G-4, G-5	
Atomic weights	C-2	
Critical temperatures and pressures	E-2	



References to Original Data

Nat. Bur. Stands. Circ. 410 (1936). (Oils 65–100° A. P. I. 0° to 90°F, oils 55–65° A. P. I. 0° to 125°F.)

Sage and Lacey, *Ind. Eng. Chem.* **34**, 730 (1942). (*n*-Pentane, 100° to 387°F.)

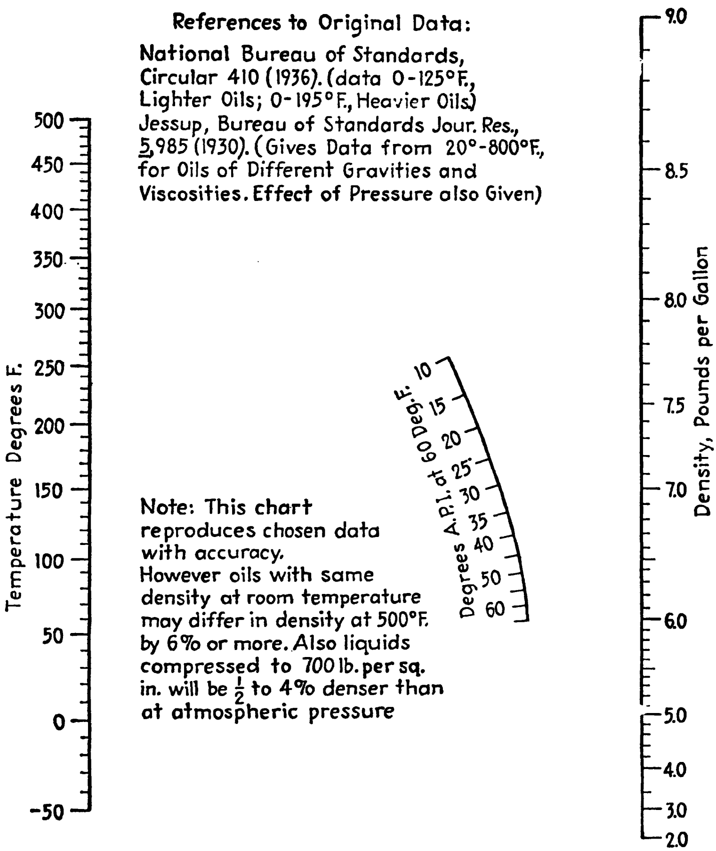
Stearns and George, *Ind. Eng. Chem.* **35**, 602 (1943). (Propane, −80° to 200°F.)

Edwards, *Refrigerating Eng.*, August, 1944. (Ethane up to 90°F.)

York and White, *Trans. Am. Inst. Chem. Engrs.* **40**, 227 (1944). (Ethylene up to 48°F.)

Carney, *Proc.*, 21st Annual Convention of the Natural Gasoline Association of America, 1942. (Propane, *i*-Butane, *n*-Butane, *i*-Pentane, *n*-Pentane, three mixtures and three natural gasolines. Temperature range, −50 to 140°F.)

FIG. D-1.—Densities of light hydrocarbon liquids.



References to Original Data:

National Bureau of Standards, Circular 410 (1936). (data 0-125°F., Lighter Oils; 0-195°F., Heavier Oils)
Jessup, Bureau of Standards Jour. Res., 5, 985 (1930). (Gives Data from 20°-800°F., for Oils of Different Gravities and Viscosities. Effect of Pressure also Given)

Note: This chart reproduces chosen data with accuracy. However oils with same density at room temperature may differ in density at 500°F. by 6% or more. Also liquids compressed to 700 lb. per sq. in. will be ½ to 4% denser than at atmospheric pressure

Fig. D-2.—Density of typical liquid petroleum products.

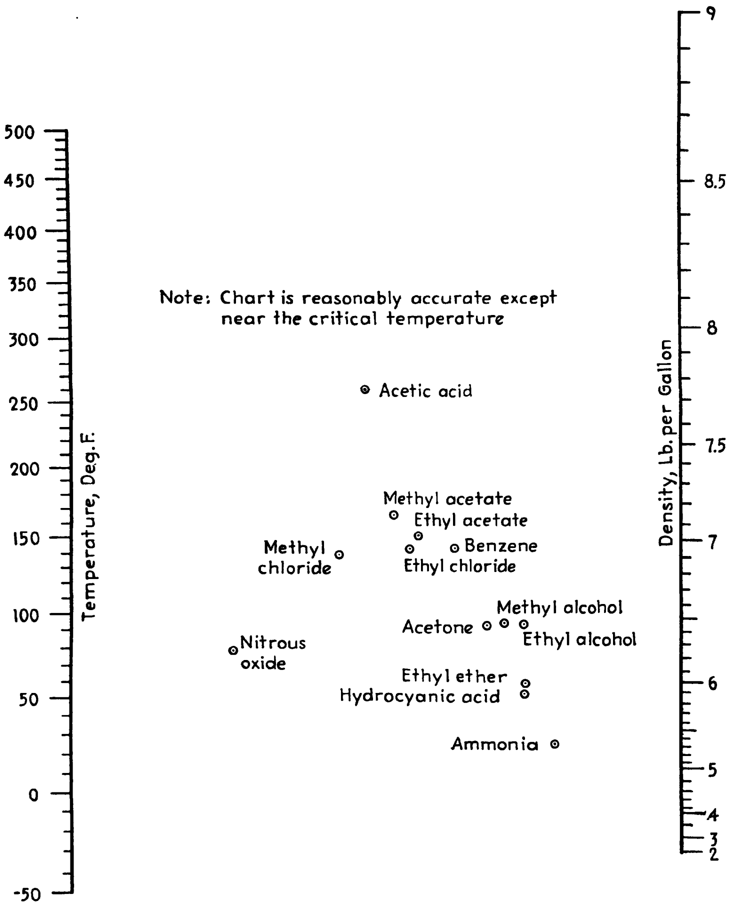


FIG. D-3.—Densities of miscellaneous liquids. (Based on data from Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York 1941; Lange, "Handbook of Chemistry," 3d ed., Handbook Publishers, Sandusky Ohio, 1939.)

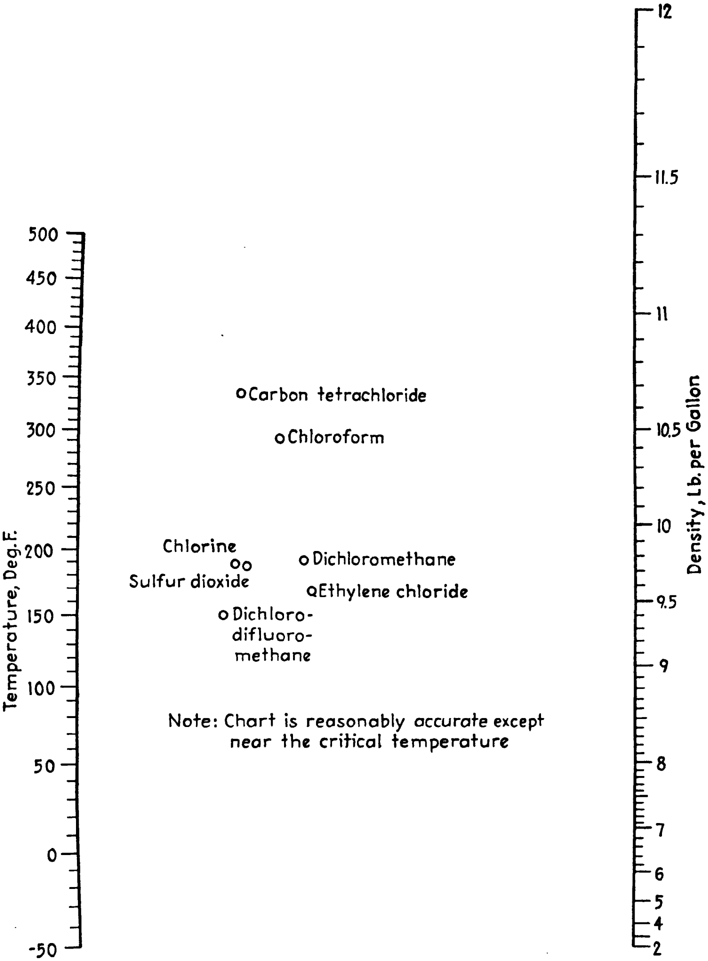


FIG. D-4.—Densities of heavy liquids. [Based on data from Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York; McGovern, *Ind. Eng. Chem.* **35**, 1230 (1943).]

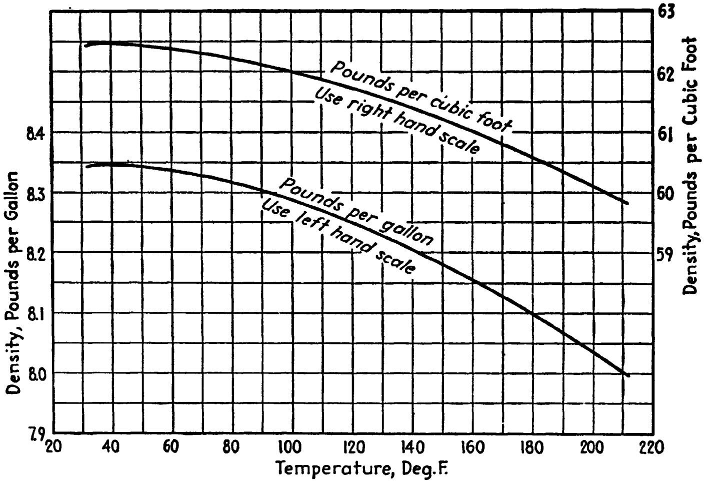
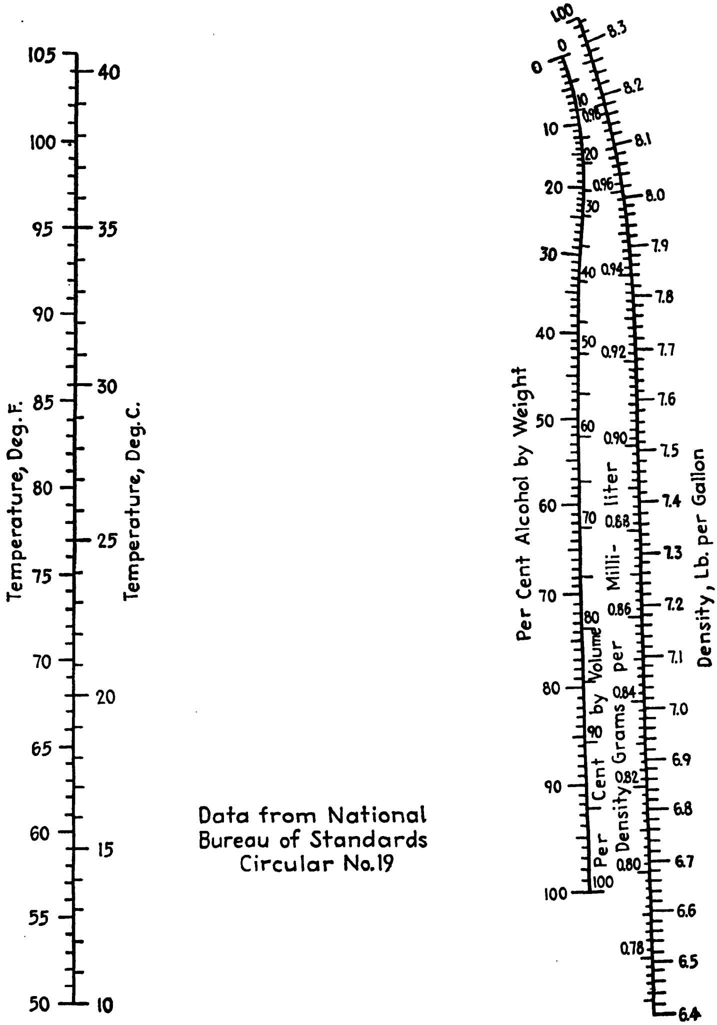
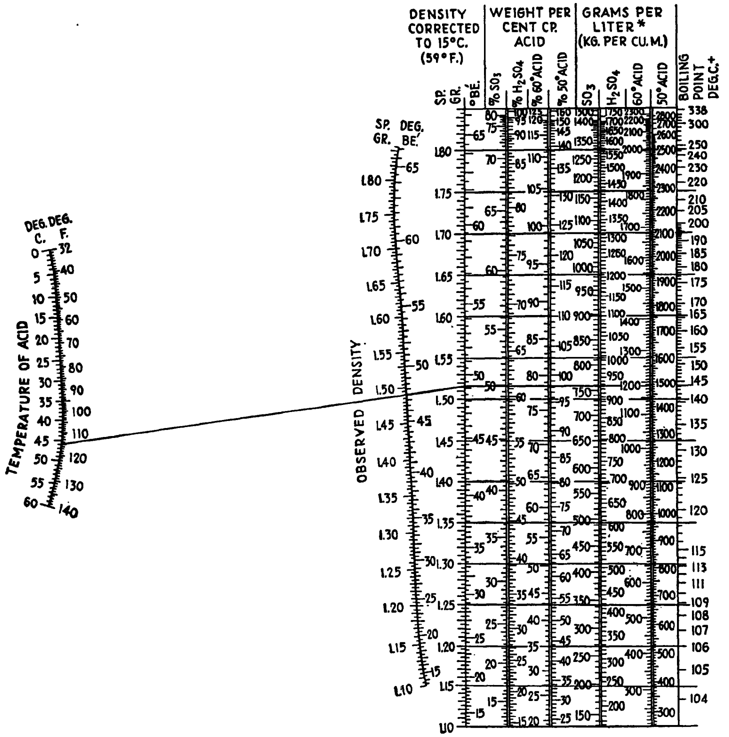


FIG. D-5.—Density of water. (Data from *Nat. Bur. Stands. Circ. No.* 19.)



Data from National Bureau of Standards Circular No.19

FIG. D-6.—Densities of ethyl alcohol water mixtures.



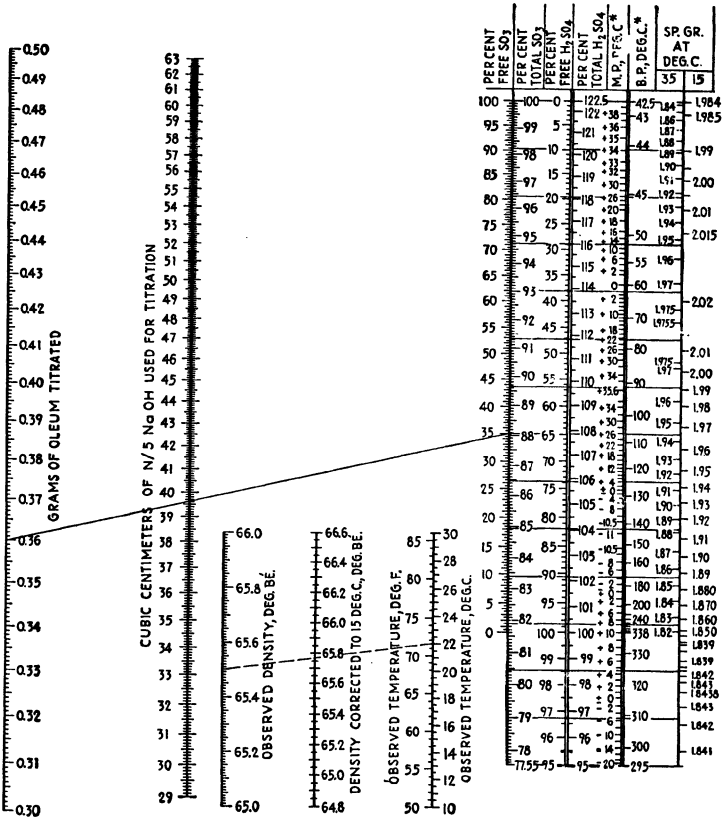
Example: A sample of sulphuric acid is tested with an hydrometer at 46°C and shows a specific gravity of 1.490 (47.5°Bé). It is desired to find the specific gravity at the standard temperature of 15°C (59°F). Using a straightedge, connect the observed temperature, 46°C, with the density read from the hydrometer, 47.5°Bé, and extend the line to the scale showing density at 15°C, cutting the scale at a specific gravity of 1.516 (49.1°Bé). To determine the physical properties of the acid corresponding with this density, extend a horizontal line from the point 1.516 on the corrected density scale, to the right, cutting the several scales showing the constants for this acid, corrected to 15°C.

The sample is thus found to contain 50 per cent SO_3, 61.3 per cent H_2SO_4, and the equivalent of 78.5 per cent of 60°, and 98.0 per cent of 50°Bé acid. It contains 758 g of SO_3 per liter, 928 g of 100 per cent H_2SO_4, and the equivalent of 1,189 g of 60° and 1,488 g of 50°Bé acid per liter. Its boiling point is 144°C.

Warning: Interconversion data for acids of 95 per cent to 100 per cent H_2SO_4 will be found in Fig. D-8 dealing with oleum. The present chart is too restricted to permit the desired accuracy in this range.

* For pounds per cubic foot, divide by 16.02.
† For degrees Fahrenheit, multiply by 1.8 and add 32.

FIG. D-7.—Nomographic chart for temperature correction of sulphuric acid densities. (*Berl, Chem. and Met. Eng., January,* 1939.)

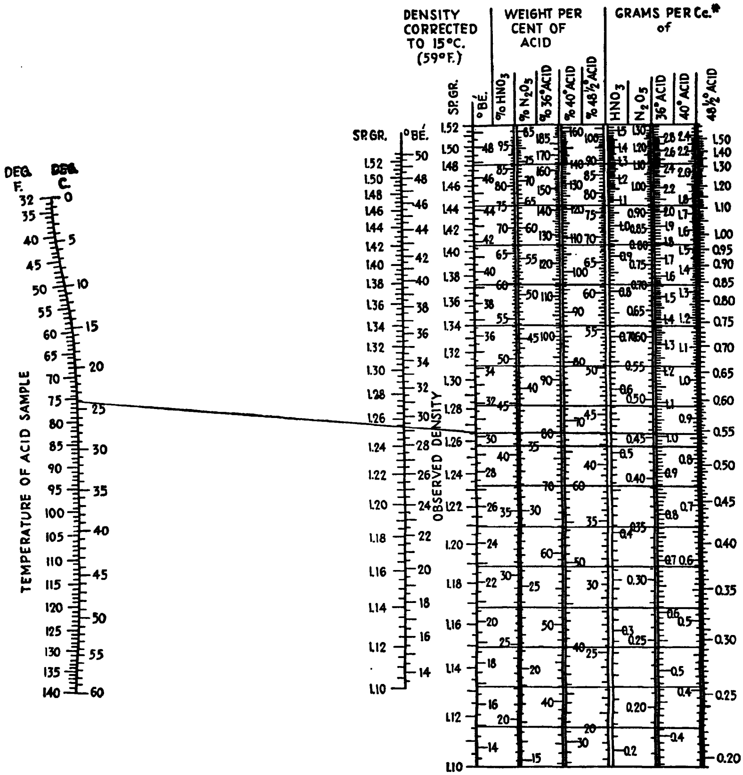


Example: A sample of oleum is titrated against N/5 NaOH, using 0.360 g of oleum and requiring 39.61 cc. of NaOH solution. With a straightedge, connect 0.360 on the left scale with 39.61 on the center scale and extend the line to 35.0 per cent free SO_3 on the first scale at the right. A horizontal line through this point shows that the sample contains 88.06 per cent total SO_3, 65.0 per cent free H_2SO_4, and 107.9 per cent total H_2SO_4. Its melting point is 25.8°C (78.4°F), its boiling point about 107°C (225°F) and its specific gravity at 15°C (59°F) about 1.967. The chart may similarly be used for sulphuric acid of strengths from 95 to 100 per cent.

The small nomograph is useful for making temperature corrections of the Baumé of H_2SO_4 of 65 to 66°. For example, as shown by the dashed line, acid measured as 65.5°Bé at 22°C is of 65.77°Bé when corrected to 15°C.

* For degrees Fahrenheit, multiply by 1.8 and add 32.

FIG. D-8.—Nomographic chart for calculating oleum analyses and for interconverting physical data of oleum. (*Berl, Chem. and Met. Eng., March,* 1939.)

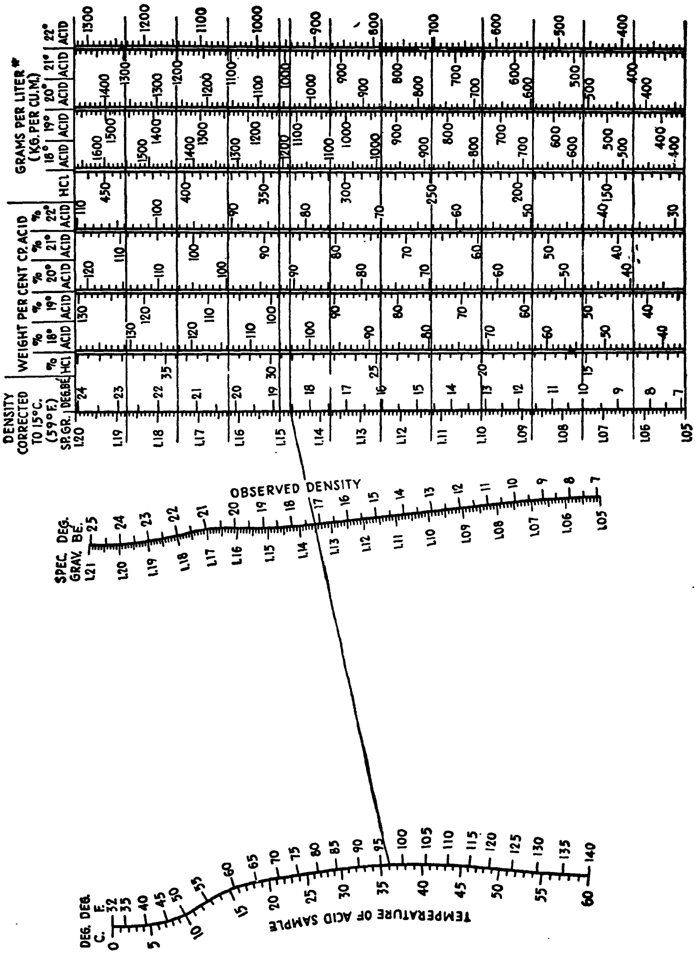


Example: A sample of nitric acid is tested with an hydrometer at 24°C and is found to have a specific gravity of 1.255 (29.3°Bé). It is desired to find the specific gravity at the standard temperature of 15°C (59°F). Using a straightedge connect the observed temperature, 24°, with the density read from the hydrometer, 29.3°Bé, and extend the line to the scale showing density at 15°C, cutting the scale at a specific gravity of 1.265 (30.2°Bé). To determine the physical properties of the acid corresponding with this density, extend a horizontal line from the point 1.265 on the corrected density scale to the right, cutting the several scales showing the constants for this acid, corrected to 15°C.

The sample is thus found to contain 42.1 per cent HNO_3, 36.1 per cent N_2O_5, and the equivalent of 79.8 per cent of 36°Bé acid, 68.1 of 40° acid and 43.2 per cent of 48½° acid. Each cubic centimeter contains 0.531 g of HNO_3, 0.457 g of N_2O_5, and the equivalent of 1.009 g of 36°Bé acid, 0.861 g of 40° acid and 0.546 g of 48½° acid.

* For pounds per cubic foot, multiply by 62.428.

FIG. D-9.—Nomographic chart for temperature correction of nitric acid density. (*Berl, Chem. and Met. Eng., April,* 1939.)

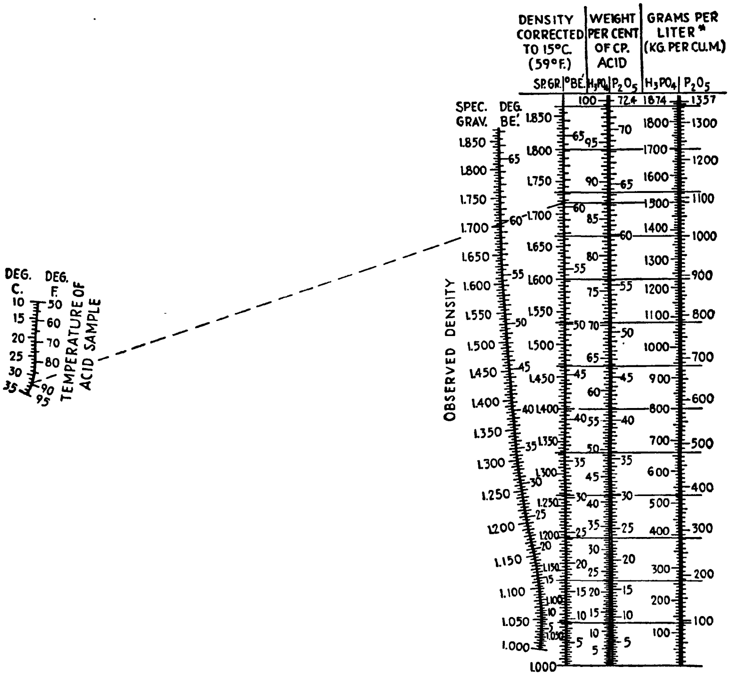


Example: A sample of hydrochloric acid is tested with a hydrometer at 36°C and shows a specific gravity of 1.135 (17.2°Bé). It is desired to find the specific gravity at the standard temperature of 15°C (59°F). Using a straightedge, connect the observed temperature, 36°, with the density read from the hydrometer, 17.2°Bé, and extend the line to the scale showing density corrected to 15°C, cutting the scale at a specific gravity of 1.1473 (18.55°Bé). To determine the physical properties of the acid corresponding with this density, extend a horizontal line to the right, cutting the several scales showing the constants for this acid.

The sample is thus found to contain 29.1 per cent HCl and the equivalent of 103.3 per cent of 18°, 97 per cent of 19°, 90.6 per cent of 20°, 86.4 per cent of 21°, and 82.1 per cent of 22°Bé acid. It contains 334 g of 100 per cent HCl per liter, and the equivalent of 1,185 g of 18°, 1,113 g of 19°, 1,039 g of 20°, 990 g of 21°, and 941 g of 22°Bé acid per liter.

* For pounds per cubic foot, divide by 16.02.

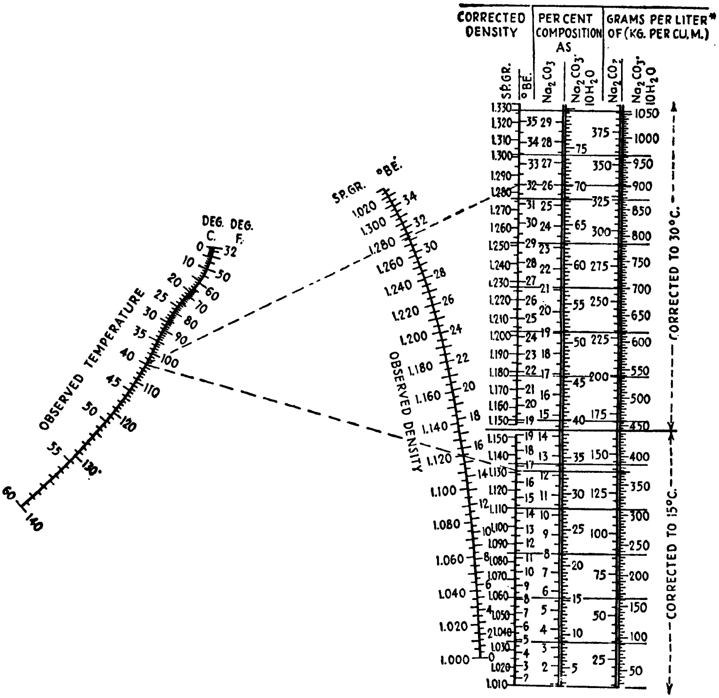
FIG. D-10.—Nomographic chart for temperature correction of hydrochloric acid densities. (*Berl, Chem. and Met. Eng., June,* 1939.)



Example: A sample of phosphoric acid is tested with a hydrometer at 32°C (89.6°F) and shows a specific gravity of 1.705 (59.7°Bé). To find the specific gravity at the standard temperature of 15°C (59°F), with a straightedge connect the observed temperature, 32°, with the observed specific gravity, 1.705, and extend the line to the corrected density scale, cutting the latter at 1.717 specific gravity (60.3°Bé). To determine the physical properties of the acid corresponding with this density, extend a horizontal line to the right, cutting the several scales showing the constants for this acid. The acid is thus found to contain 87.2 per cent H_3PO_4 and the equivalent of 63.2 per cent of P_2O_5. In each liter are 1,498 g of 100 per cent H_3PO_4 and the equivalent of 1,087 g of P_2O_5.

* For pounds per cubic foot, divide by 16.02.

FIG. D-11.—Nomographic chart for temperature correction of phosphoric acid densities. (*Berl, Chem. and Met. Eng., July,* 1939.)



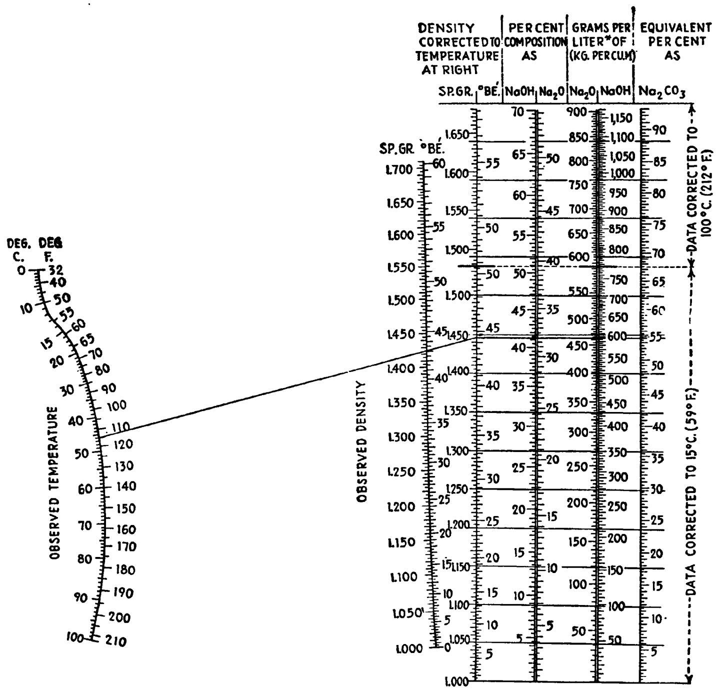
This chart differs from other ones in this series in that the correction scales are in two parts, one for corrections to a standard temperature of 15°C and the other for corrections to 30°C. The two sections of the chart are separated by the heavy black line which divides the vertical scales at the right. Solutions of more than 1.150 sp gr become supersaturated above 15°C. Hence, for solutions below 1.150 sp gr use the lower scales with a standard temperature of 15°C. For solutions above 1.150 sp gr use the upper scales with a standard temperature of 30°C.

Examples: A solution of soda ash tested with a hydrometer at 40°C shows a specific gravity of 1.120 (15.45°Bé). It is desired to find the specific gravity corrected to 15°C (59°F), and also the composition and the grams per liter (kilograms per cubic meter) in terms of Na_2CO_3 (soda ash) and $Na_2CO_3.10\ H_2O$ (sal soda). With a straight edge connect the observed temperature, 40°, with the observed density, 1.120 sp gr, and extend the line to the scale for density corrected to 15°C, cutting the latter at 1.131 sp gr (16.7°Bé). To determine the physical properties corresponding to this corrected density, extend a horizontal line from 1.131 to the right. The sample is thus found to contain 12.2 per cent Na_2CO_3 and 33.0 per cent $Na_2CO_3.10\ H_2O$. It contains 138 g per l (kg per cu m) of Na_2CO_3 and 373 g per l of $Na_2CO_3.10\ H_2O$.

Another sample of soda ash solution tested with a hydrometer at 40°C shows a density of 1.277 sp gr (31.3°Bé). By the method shown above, but using the upper section of the vertical scales, the sample corrected to 30°C is found to have a density of 1.285 sp gr (32.0°Bé). The solution contains 26.0 per cent Na_2CO_3 and 70.1 per cent $Na_2CO_3.10\ H_2O$; and 334 g per l of Na_2CO_3 and 903 g per l of $Na_2CO_3.10\ H_2O$.

* For pounds per cubic foot, divide by 16.02.

FIG. D-12.—Nomographic chart for temperature correction of sodium carbonate (soda ash) solutions. (*Berl, Chem. and Met. Eng., August,* 1939.)



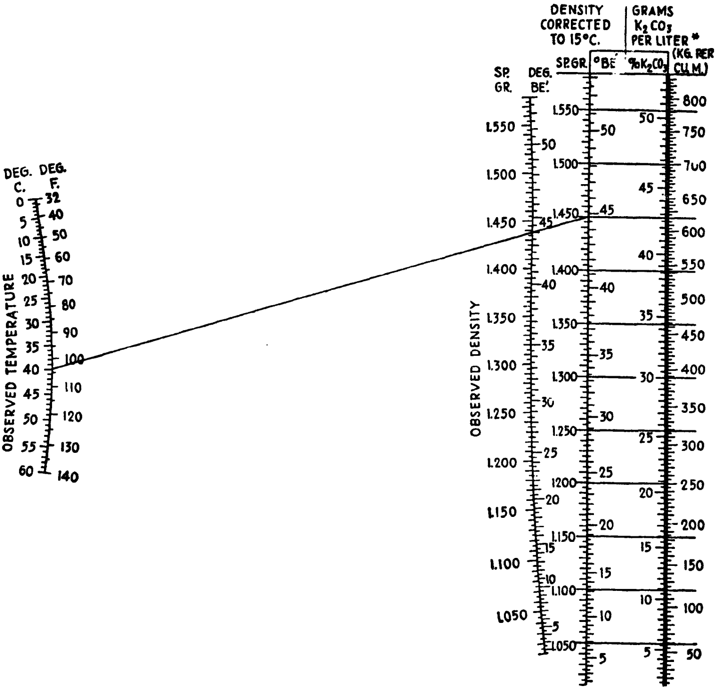
This chart differs from Figs. D-7 to D-11 and is similar to Fig. D-12 of this series in that the correction scales are in two parts, one for correction to a standard temperature of 15°C (59°F) and the other for corrections to a standard temperature of 100°C (212°F). The two sections of the chart are separated by the heavy lines indicating discontinuity in the scales for corrected density and grams per liter. Caustic soda solutions up to 51 per cent NaOH are liquid at 15°C (and some percentages considerably below this figure). Solutions of more than 51 per cent NaOH have a rising solubility curve and must be measured at a higher temperature. All concentrations to 70 per cent remain liquid at 64°C and above. Since the few available data at high concentrations are at 100°C, this temperature has been taken as standard for concentrations of 51 per cent and above.

Example: A solution of caustic soda is tested with a hydrometer at 46°C and shows a specific gravity of 1.425 (43°Bé). It is desired to find the specific gravity and Baumé corrected to 15°C (59°F) and also the composition and grams per liter (kilograms per cubic meter) in terms of NaOH and Na_2O and the equivalent percentage composition as sodium carbonate. With a straightedge connect the observed temperature, 46°, with the observed specific gravity, 1.425, and extend the line to the corrected density scale for 15°C standard temperature, cutting the latter at a gravity of 1.446 (44.5°Bé). To determine the physical properties corresponding to the corrected density extend a horizontal line to the right, cutting the several scales at the desired quantities. Thus it is found that the sample contains 41.3 per cent NaOH and 32 per cent Na_2O. It contains 462.5 g per l (kilograms per cubic meter) of Na_2O and 597 g per l of NaOH. The equivalent percentage as Na_2CO_3 is 54.7.

Warning: Corrections of solutions containing over 51 per cent of NaOH are handled exactly as above. However, the data for such solutions are not complete and the completion of the chart above the heavy lines was partly by extrapolation. Consequently accuracy equal to that for solutions of less than 51 per cent cannot be expected.

* For pounds per cubic foot, divide by 16.02.

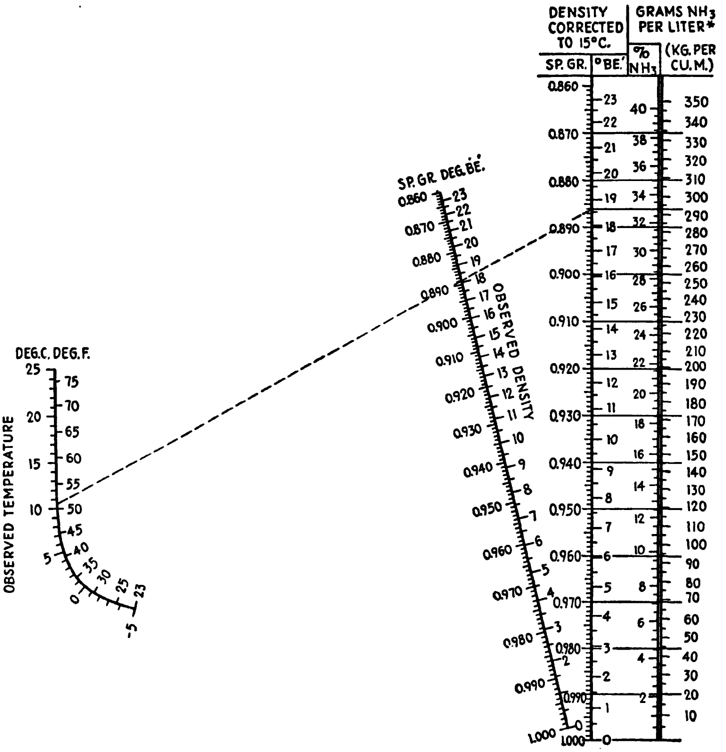
FIG. D-13.—Nomographic chart for the temperature correction of sodium hydroxide (caustic soda) solution densities. (*Berl, Chem. and Met. Eng., September*, 1939.)



Example: A sample of K_2CO_3 solution is tested with a hydrometer at 40°C, showing a specific gravity of 1.438 (44 deg. Bé.). It is desired to find the gravity corrected to 15°C, the percentage of K_2CO_3 and the quantity of K_2CO_3 per unit volume of solution. With a straightedge connect the observed temperature of 40°C with the observed specific gravity of 1.438 and extend the line to the corrected density scale, cutting the latter at a specific gravity of 1.450 (44.8°Bé) at 15°C. Extending a horizontal line from this point, note that the sample contains 42.7 per cent K_2CO_3 while each liter contains 620 g of K_2CO_3 (620 kg per cu m).

* For pounds per cubic foot, divide by 16.02.

FIG. D-14.—Nomographic chart for the temperature correction of potassium carbonate solution densities. (*Berl, Chem. and Met. Eng., November,* 1939.)



Example: A sample of aqua ammonia is tested with a hydrometer at 10.5°C, showing a specific gravity of 0.889 (18.1°Bé). It is desired to find the specific gravity corrected to 15°C, as well as the Baumé at this temperature and the per cent NH_3 and grams of NH_3 per liter (kilograms per cubic meter). With a straightedge connect the observed temperature, 10.5°C, with the observed specific gravity, 0.889, and extend the line to the corrected density scale, cutting the latter at a specific gravity of 0.886 (18.6°Bé), the density corrected to 15°C. To determine the physical properties corresponding to this density, extend a horizontal line to the right to intersect the scales for composition and grams per liter. Thus it is found that the sample contains 33.0 per cent NH_3 and 293 g of NH_3 per liter (kilograms per cubic meter).

* For pounds per cubic foot, divide by 16.02.

FIG. D-15.—Nomographic chart for the temperature correction of aqua ammonia densities. (*Berl, Chem. and Met. Eng., December,* 1939.)

2. Metals

a. Mechanical Tests.—For ductile, resilient materials such as structural steel the tensile stress-strain test is the most important. This test consists in applying a force (stress) to a standard specimen and measuring the elongation (strain). The force is gradually increased until failure of the specimen occurs. The results of such a test are shown in Fig. D-16. The slope of the line *OA*, *i.e.*, the ratio of stress to strain below the proportional limit, is *Young's modulus of elasticity*. The *proportional limit* is the highest stress at which the strain is proportional to the stress. (By common consent, stresses are almost universally expressed as pounds per square inch of original cross section.) At stresses above this limit the specimen is permanently deformed. The definitions of *yield point*, *ultimate tensile strength*, and *breaking strength* are indicated by Fig. D-16. Many materials do not exhibit yield points. In these cases the *yield strength* or stress to produce a standard permanent deformation (per cent set) is usually specified. A method commonly used to determine the yield strength is the offset method, illustrated by Fig. D-17. Very common practice is to base the yield strength on 0.2 per cent set, though for some materials or for special uses the design engineer may prefer yield strengths based on smaller or larger sets.

Compressive strength tests are made in much the same way as tensile tests. For iron and steel products, the yield strength in tension and compression are nearly the same, though the ultimate strengths differ. Metals are also tested by applying stress in other ways, notably in shear.

The rate of applying stress to a metal may be of importance. For example, brittle materials may have high tensile strengths but may fracture readily under sharp blows. Impact tests such as the Izod and several varieties of Charpy are, therefore, of importance in design where brittle materials must be employed. It should perhaps be noted that some materials, such as iron and lead which are ductile at room temperature, become brittle at low temperatures.

Soft materials such as lead exhibit a slow deformation at comparatively low stress. This phenomenon is known as "creep" and is exhibited by all metals at high temperatures. The rate of creep usually exhibits three stages: The initial rate is comparatively rapid and drops slowly to a steady rate in the second stage. Eventually the rate increases in the third stage which ends in failure. Results are usually presented as the stress that produces a specified creep rate in the second stage.

Failure of metals (even though creep is not measurable) may occur

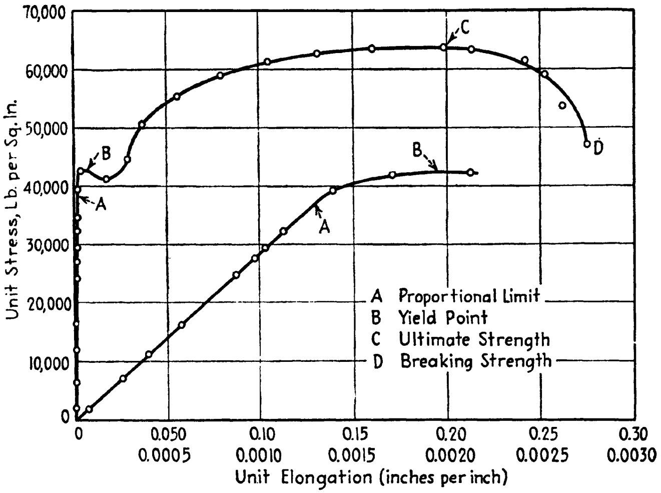


FIG. D-16.—Stress-strain diagram for a specimen of ductile steel. Lower curve is part of upper curve drawn to larger horizontal scale. (*Reprinted by permission from "Properties and Mechanics of Materials," by P. G. Laurson and W. J. Cox, published by John Wiley & Sons, Inc., New York,* 1931.)

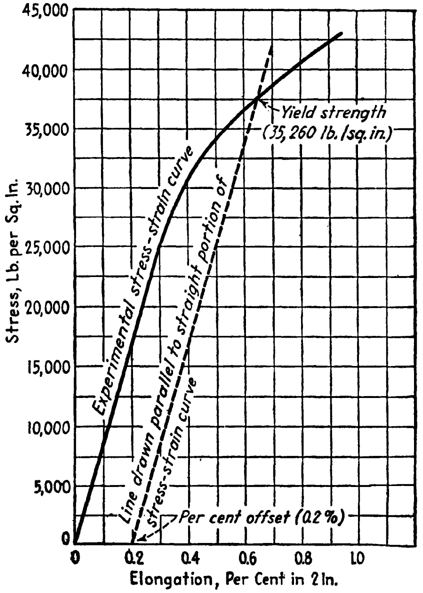


FIG. D-17.—Illustration of yield-strength determination by offset method.

far below the tensile strength if the stress is repeated many times. For this reason repeated stress tests are important. The results of such tests show that there is a limiting stress below which no failure will occur no matter how often applied. This *endurance* limit can be obtained graphically from a series of tests.

Obviously the above discussion has covered only a few tests in broad terms. These and many more tests have been carefully standardized by technical societies such as the American Society of Testing Materials (A.S.T.M.) and the American Society of Mechanical Engineers (A.S.M.E.). Most of the standards in use in the United States are catalogued and sold by the American Standards Association (A.S.A.).

In addition to data on properties of finished products, the design engineer requires information on the fabricating methods that may be employed—whether the metal is readily machined, welded, soldered, pressed, drawn, forged, etc.

Mechanical properties of metals depend on an extremely large number of variables. Some of these are listed below:

1. Chemical analysis (even small quantities of alloying element may be important).
2. Method of manufacture (cast, wrought, etc.).
3. Heat-treatment (annealing, quenching, drawing).
4. Mechanical processing (hot-rolling, cold-drawing, etc.).
5. Surface treatment (casehardening, finish, etc.).
6. Corrosion.

b. Wall Thickness of Vessels and Piping.—The fundamental purpose of mechanical tests is to afford a basis for mechanical design. The mechanical engineer wants to know how heavy the beams of a bridge must be to support the load. The chemical engineer wishes to know how heavy the shell of an autoclave must be to withstand the temperature, pressure, and corrosive nature of the contents. Below are given two formulas for the minimum shell thickness of cylindrical walls:

$$t_m = \frac{PD}{2S} + C \quad \text{(Barlow's formula, modified)}$$

$$t_m = \frac{D}{2}\left(1 - \sqrt{\frac{S - P}{S + P}}\right) + C \quad \text{(Lamé's formula)}$$

where t_m = minimum wall thickness, in.
D = outside diameter of pipe, in.
S = design stress, psi
P = internal pressure, psig

C = allowances, in., for threading, mechanical strength, machining, corrosion

Barlow's formula is accurate for only thin wall vessels and may be used when the wall thickness is 10 per cent or less of the outside diameter. For thicker wall vessels Lamé's formula is applicable. (Even this formula fails, however, for high pressures where P is nearly as large as S.) In the case of piping the following very simple formula may be employed:

$$\text{Schedule number} = \frac{1{,}000P}{S}$$

where P = internal pressure, psig
S = design stress, psi

Some design stresses for use in the above formulas are given in the next section. Detailed discussion of the considerations involved in choice of design stresses is beyond the scope of this book. The A.P.I.—A.S.M.E. codes cover these for a variety of metals in different uses. In any event, the *code legal in the locality should be consulted for final engineering design.* For a great many purposes one-fourth of the ultimate tensile strength is used as the design stress. For brittle materials, higher factors of safety must be employed.

In general, elliptical ends, flanges, etc., must be heavier than the walls of a vessel. However, given formulas permit the process engineer to judge whether his process involves unduly heavy equipment.

c. Data Tables.

TABLE D-1.—LISTING OF TABLES ON PROPERTIES OF METALS

	Metals							
Properties	Low-carbon steel	4/6 Cr Mo cast steel	Stainless steels	Monel	Copper alloys	Aluminum (17 S-T)	Lead	Other
Density, thermal conductivity, specific heat	D-2	....	D-2	D-2	D-2	D-2	D-2	D-2
Coefficient of expansion	D-2, D-3	....	D-2, D-9	D-2	D-2	D-2	D-2	D-2
Tensile tests	D-3	D-4	D-8	D-11	....	D-12		
Creep stress	D-3	D-4	D-8	D-11				
Endurance limit	....	....	D-8	....	....	D-12		
Design stress	D-5	....	D-10	....	D-6	....	D-13	
Impact tests	D-7							

TABLE D-2.—REPRESENTATIVE PROPERTIES OF METALS
(Compiled from several sources)

Metal	Specific gravity (water = 1 at 60°F)	Coefficient of expansion, ft/(1,000,000 ft)(°F)	Thermal conductivity, Btu/(hr)(sq ft)(°F/ft)	Specific heat, Btu/(lb)(°F)
Aluminum	2.7	12.7	118‡	0.226
Antimony	6.6	6.3	11	0.049
Bismuth	9.8	7.5	4.7	0.029
Chromium	7.2	4.7	157	0.12
Cobalt	8.9	6.7	40	0.098
Copper:				
Pure copper	8.9	9.3	220‡	0.092
Admiralty and 70% brass	8.5	10.3	58‡	
Muntz and yellow brass	8.4	11.6	70	0.092
Red brass	8.6–8.75	9.8–10.4	90–94	
Bronze	8.8	9.8	100	
Everdur	8.2	7.8	16	
Monel	8.8	7.8	15	0.127
Iron:				
Pure iron	7.9	6.6	38‡	0.1045
Wrought iron	7.7	....	33‡	
Low-carbon steel	7.8	6.1–7.3*	35‡	0.11
High-carbon steel	7.8	6.1–7.3*	26‡	0.12
Gray cast iron	7.0–7.7	10	24–30‡	0.13
18–8 Cr-Ni	7.9	9.5†	9.6‡	0.117
25–12 Cr-Ni	7.9	8.3	8.8	0.12
12% Cr	7.7	5.8	14.3‡	0.11
Lead	11.3	16.4	19‡	0.030
Magnesium	1.74	14.3	92	0.249
Monel	8.8	7.8	15	0.127
Nickel	8.9	7.3	35‡	0.112
Silver	10.5	10.5	240	0.056
Sodium	0.97	39.5	26	0.295
Tantalum	16.6	3.6	35	0.036
Tin	7.3	11.2	34	0.054
Vanadium	19.3	2.2	115	0.034
Zinc	7.1	18.3	64	0.089

* Additional data given in Table D-3.

† Additional data given in Table D-9.

‡ Additional data given in Table G-4.

Table D-3.—Properties of Killed Carbon Steel

(Reprinted from Hoyt, "Metals and Alloys Data Book," Reinhold Publishing Corporation, New York, 1943, by permission of the author, publisher, and the Steel and Tube Division of The Timken Roller Bearing Company)

Composition: 0.10–0.20% C, 0.30–0.60% Mn, 0.25% Si max., 0.04% P max., 0.045% S max.

Temp., °F	Tensile strength	Yield strength 0.2% set	Proportional limit	Elongation, % in 2 in.	Reduction in area, %	Creep stress, 1%		Rupture stress*	Coefficient of expansion† ft/(1,000,000 ft)(°F)
						100,000 hr	10,000 hr		
85	62.4	42.0	34.5	36	67				
750	58.0	24.6	13.1	34	67				
800	....	....	....	..	..	18.5	26.8	...	7.83
900	45.5	23.5	11.2	38	71	12.8	16.9	...	7.95
1000	36.5	20.1	8.7	42	77	2.7	5.7	2.8	8.02
1100	27.2	14.2	5.0	56	82	0.8	1.8	...	8.21
1200	20.0	10.2	1.9	54	89	0.3	0.6	0.6	8.36
1300	13.5	7.4	0	60	92	....	....	0.4	
1400	9.0	3.7	0	70	77	....	....	0.2	

Note: All stresses are in units of 1,000 psi.

* Stress to produce rupture in 100,000 hr.

† Mean coefficient from 70°F to stated temperature.

Table D-4.—High-temperature Tests of 4/6 Cr-Mo Cast Steels (A.S.T.M.-A.S.M.E. "Creep Data")

(Hoyt, "Metals and Alloys Data Book," Reinhold Publishing Corporation, New York, 1943)

Analysis, %: C, 0.31; Mn, 0.57; Si, 0.37; Cr, 4.86; Mo, 0.53. Normalized at 1650°F; drawn at 1300°F.

Temp., °F	Tensile strength, thousands of psi	Yield point, thousands of psi	Proportional limit, thousands of psi	Elongation, % in 2 in.	Reduction in area, %	Creep stress for 1% in 10,000 hr, thousands of psi
70	118	90	71	17	44	
300	111	89	77	14	43	
550	103	78	68	13	41	
800	101	70	52	12	37	
900	...	..	..	..	..	18
1000	73	56	38	21	58	10
1200	45	18	..	37	82	

Note: Yield point = yield strength for 0.2 per cent set.

TABLE D-5.—DESIGN STRESSES FOR STEEL
(Hoyt, "Metals and Alloys Data Book," Reinhold Publishing Corporation, New York, 1943)

	Tensile strength, %*		
Metal temp., °F	Cast steel	C-steel plates	C-Mo steel
Room	16.7	25	25
650	16.7	25	25
700	16.4	23.7	25
750	14.7	21.0	25
800	12.9	18.0	24.3
850	11.1	15.0	22.4
900	9.3	12.0	18.3
950	7.5	9.0	13.7
1,000	5.7	6.2	9.5

* Per cent of tensile strength at room temperature.

NOTE: The values for cast steel and steel plates are from the A.P.I.-A.S.M.E. Pressure Vessel Code. The values for plates (and forgings) apply to steels for which the minimum of the specified tensile strength is not over 55,000 psi. For carbon steels of a higher tensile strength the calculated design stress may be used, provided the stresses above 700°F are based on the tensile strength of the annealed material. For A.S.T.M. steels A149 and A150, the allowable working stresses for temperatures above 750°F are the same as those for steels whose minimum tensile strength is 55,000 psi.

The values for C-Mo steel plates (0.50 per cent Mo) are recommended by T. M. Jasper.

TABLE D-6.—ALLOWABLE WORKING STRESSES FOR COPPER ALLOYS
(Based on A.S.M.E. Boiler Construction Code. Reprinted from Hoyt, "Metals and Alloys Data Book," Reinhold Publishing Corporation, New York, 1943)

Material	Allowable working stresses, psi, for temperatures not over				
	150°F	250°F	350°F	400°F	450°F
Muntz metal and high-brass tubing, and condenser tubes	5,000	4,000	2,500		
Red brass tubes	6,000	5,500	5,000	4,500	
Copper tubes and pipes	6,000	5,000	4,500	4,000	
70–30 brass condenser tubes	6,000	5,000	4,500	4,000	
Admiralty tubes	7,000	6,500	6,000	5,500	4,500

NOTE: These apply only to diameters from ½ to 6 in. OD inclusive, and for wall thicknesses not less than 0.049 in. (No. 18 B.W.G.).

Table D-7.—Charpy Impact Tests on Bessemer Steel, Killed
(Hoyt, "Metals and Alloys Data Book," Reinhold Publishing Corporation, New York, 1943)

Seamless pipe 10¾ in. OD × ½ in. wall.

Si, Mn, Al, killed. 0.15% C, 0.47% Mn, 0.22% Si, 0.074% P, 0.017% N, tested as normalized. McQuaid-Ehn grain size, 4–8.

Tensile strength, psi	67,500
Yield strength, psi	48,000
Elongation, %	47.5
Reduction in area, %	55.5
Charpy impact test, ft-lb at	
70°F	47
32°F	40
0°F	36
−25°F	34
−50°F	21

Table D-8.—Endurance Limits, Creep Stress, etc., of Stainless Steel
(By H. C. Cross, Battelle Memorial Institute. Reprinted from Hoyt, "Metals and Alloys Data Book," Reinhold Publishing Corporation, New York, 1943)

Property	Units	Steel No. 1	Steel No. 2	Steel No. 3	Steel No. 4
Analysis	%	C....... 0.067 Cr...... 18.21 Ni...... 9.56 N....... 0.056		C........ 0.125 Cr....... 18.50 Ni....... 9.67 N........ 0.035	
Form	....	Rolled bars	Cast bars	Rolled bars	Cast bars
Brinell hardness	....	155	137	160	131
Tensile properties at room temperature:					
Tensile strength	Psi	85,000	64,500	91,000	64,500
Yield strength	Psi	36,500	28,000	41,000	31,200
Elongation	% in 2 in.	62	66	60	59
Reduction in area	%	70	..	71	
Izod impact	Ft-lb	105	92	107	93
Endurance limit tested at 2,500 rpm:					
At room temp	Psi	40,000	36,000	42,000	35,000
At 800°F	Psi	32,000	......	37,000	
At 1000°F	Psi	32,000	......	38,000	
At 1200°F	Psi	30,000	20,000	32,000	23,000
Creep stress:					
1% elong. in 10,000 hr					
At 1000°F	Psi	20,000	>17,300	25,000	22,500
At 1100°F	Psi	14,000	....	17,300	17,000
At 1200°F	Psi	8,200	8,500	10,500	9,300

Note: One-inch bars were water-quenched from 2000°F.

TABLE D-9.—THERMAL EXPANSION OF STAINLESS STEEL*
(Data of Babcock and Wilcox Tube Co. Reprinted from Hoyt, "Metals and Alloys Data Book," Reinhold Publishing Corporation, New York, 1943)

Steel	Temp., °F	Mean coefficient of linear expansion, ft/(1,000,000 ft)(°F)
18-8 Cr-Ni	68– 600	9.88
	68– 800	10.08
	68–1000	10.20
	68–1200	10.41
	68–1300	10.50
	68–1800	11.25
16-13-3 Cr-Ni-Mo	75– 400	9.60
	75– 800	10.20
	75–1000	10.50
	75–1200	10.80
25-20 Cr-Ni	105–1320	9.20
	70–1830	10.60

* Considering commercial variations, these values may vary as much as 0.50.

TABLE D-10.—DESIGN STRESSES FOR WROUGHT HEAT-RESISTING ALLOY STEELS
(Courtesy of the Midvale Company)
Analysis range: 25–30% Cr, 10–30% Ni

Temperature, °F	1,400	1,500	1,600	1,700	1,800	2,000
Design stress, psi	1,800	1,550	1,300	1,050	800	300

TABLE D-11.—HIGH-TEMPERATURE PROPERTIES OF MONEL
(Hoyt, "Metals and Alloys Data Book" Reinhold Publishing Corporation, New York, 1943)

Temp., °F	Short-time tests			Creep tests		
	Yield strength, (0.2% set) psi	Tensile strength, psi	Elongation, % in 2 in.	0.01%/ 1,000 hr, psi	0.1%/ 1,000 hr, psi	1%/1,000 hr, psi
70	45,000	85,000	45			
600	34,000	80,000	44	26,000	36,000	46,000
800	30,000	70,000	40	19,000	23,500	29,000
1000	27,000	55,000	30	1,650	4,300	11,500
1200	23,000	36,000	18			1,700

TABLE D-12.—ENDURANCE LIMIT AND TENSILE STRENGTH OF 17 S-T* ALLOY ALUMINUM

(By F. M. Howell and E. S. Howarth. Reprinted from Hoyt, "Metals and Alloys Data Book," Reinhold Publishing Corporation, New York, 1943)

	Test temp., °F			
	75	300	400	500
Days heated before tensile test	......	250	200	200
Tensile strength, psi	59,000	40,200	25,000	12,800
Yield strength, psi (0.2% set)	36,000	33,500	20,000	9,700
Elongation, % in 2 in	24	17	25	38
Days heated before fatigue test	......	200	100	100
Endurance limit, psi†	15,000	13,500	9,500	4,500

* 17S specifies analysis (Aluminum Co. of America): 4.0% Cu, 0.5% Mn, 0.5% Mg. 17 S-T is fully heat-treated.

† Rotating-beam test on basis of 500,000,000 cycles at 3,600 rpm.

TABLE D-13.—ALLOWABLE STRESS IN EXTRUDED LEAD PIPE

(Hoyt, "Metals and Alloys Data Book," Reinhold Publishing Corporation, New York, 1943)

Temp., °F	Allowable stress, psi	
	Chemical lead	6% antimony lead
68	200	400
86	190	370
104	180	340
122	172	310
140	162	280
158	153	254
176	144	222
194	136	195
212	127	165
230	118	137
248	110	110
266	100	80
284	90	50
302	80	

3. Nonmetallics

a. Ceramics and Stone.—Properties of ceramics and stone are presented as follows:

Strengths of brick and terra-cotta block piers.......... Table D-14
Physical properties of refractory materials............ Table D-15
Strength and stiffness of American building stone...... Table D-16
Physical properties of low-expansion glass, fused silica and fused quartz.............................. Table D-17
Physical properties of chemical stoneware............ Table D-18

TABLE D-14.—STRENGTH IN COMPRESSION OF BRICK AND OF TERRA-COTTA BLOCK PIERS AND WALLS

(Moore, "Textbook of the Materials of Engineering," 6th ed., McGraw-Hill Book Company, Inc., New York, 1941)

The values given are based on test data from Watertown (Mass.) Arsenal, Cornell University, U.S. Bureau of Standards, and the University of Illinois.

The weight of masonry may be taken as about 5 lb/cu ft less than the weight of the stone or brick used.

Brick or block used	Mortar	Ultimate in compression, psi
	Piers	
Vitrified brick	1 part portland cement, 3 parts sand	2,800
Pressed (face) brick	1 part portland cement, 3 parts sand	2,000
Pressed (face) brick	1 part lime, 3 parts sand	1,400
Common brick	1 part portland cement, 3 parts sand	1,000
Common brick	1 part lime, 3 parts sand	700
Terra-cotta block	1 part portland cement, 3 parts sand	3,000
	Walls	
Common brick	1 part portland cement, 1¼ parts lime, 6 parts sand	950
Common brick	1 part portland cement, 3 parts sand	1,150
Hollow-tile joints staggered	1 part portland cement, ¼ part lime, 3 parts sand	1,270

Test data for piers built of sand-lime brick are lacking, but judging from test data for individual brick, sand-lime brick piers might be expected to be about three-quarters as strong as piers built of common brick.

TABLE D-15.—PHYSICAL PROPERTIES OF REFRACTORY MATERIALS

(Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York, 1941. Complete revision of earlier *Chem. & Met. Eng.* data, compiled by L. J. Trostel, General Refractories Co., Baltimore, with additional material on kaolin superduty and insulating refractories supplied by the Babcock & Wilcox Co., New York)

	Type of brick												
	Silica	High-heat duty (No. 1) fire clay	Super-duty fire clay	Super-duty kaolin	Alumina-diaspore, 70% Al_2O_3	Silli-manite (mullite)	Chrome	Unburned chrome[a]	Magne-site	Unburned magnesite[a]	Bonded silicon carbide, grade A	Bonded fused alumina	Kaolin insulating refractory, 2600°F
Typical composition, %:													
SiO_2	96	50–57	52	52	22–26	35	6	5	3	5	7–9	8–10	57.7
Fe_2O_3	1	1.5–2.5	1	0.6	1–1.5	0.5	...	...	6	8.5	0.3-1	1–1.5	2.4
FeO	...	...	...	...	...	...	15	12					
Al_2O_3	1	36–42	43	45.4	68–72	62	23	18	2	7.5	2–4	85–90	36.8
TiO_2	...	1.5–2.5	2	1.7	3.5	1.5	...	...	...	...	1	1.5–2.2	1.5
CaO	2	...	...	0.1	...	...	...	...	3	2	...	...	0.6
MgO	...	...	...	0.2	...	...	17	32	86	64	...	...	0.5
Cr_2O_3	...	...	...	...	...	...	38	30	...	10			
SiC	...	...	...	...	...	...	...	...	...	...	85–90		
Flux[b]	...	1–3.5	2	...	1–1.5	0.5	...	...	...	...	1.5	0.8–1.3	
P.C.E.[c]	31–32	31–33	33–34	34	36	37–38	41+	41+	41+	41+	39	39+	29–30
Approx. equivalent temp., °F	(3056–3092°)	(3056–3173°)	(3173–3200°)	(3200°)	(3290°)	(3308–3335°)	(3578°+)	(3578°+)	(3578°+)	(3578°+)	(3389°)	(3389°+)	(2984–3002°)
Deformation under load,[d] %(at psi and temp., °F, shown)	Shears (25 psi, 2900°)	2.5–10* (25 psi 2460°)	2–4† (25 psi 2640°)	0.5† (25 psi 2640°)	1–4† (25 psi 2640°)	0.0–0.5† (25 psi 2640°)	Shears (28 psi 2740°)	Shears (28 psi 2955°)	Shears (28 psi 2765°)	Shears (28 psi 2940°)	0–1 (50 psi 2730°)	1 (50 psi 2730°)	0.3 (10 psi 2200°)
Resistance to spalling, % loss in appropriate A.S.T.M. panel test	Poor	5–20	0–4	No loss	No loss	No loss	Poor	Fair	Poor	Fair	Good	Good	Good
Permanent linear change on reheating[e] (after 5 hr at temp., °F, shown)	(+)0.5–0.8 (2640°)	(±)0–1.5 (2550°)	(±)0–1.5 (2910°)	(−)0.75–1 (2910°)	(−)2–4 (2910°)	(−)0–0.8 (2910°)	(−)0.5–1 (3000°)	(−)0.5–1.0 (3000°)	(−)1–2 (3000°)	(−)0.5–1.5 (3000°)	(+)2[f] (2910°)	(+)0.5 (2910°)	(−)0.2 (2600°)
Porosity (as open pores), %	20–30	15–25	12–15	18	34–38	20–25	20–26	10–12	20–26	10–12	13–28	20–26	75
Weight per brick (std. 9 in. straight), lb	6.5	7.5	8.5	7.7	7.5	8.5	11	11.3	10	10.7	8–9.3	9–10.6	2.25
Specific heat (60–1200°F)	0.23	0.23	0.23	0.22	0.23	0.23	0.20	0.21	0.27	0.26	0.20	0.20	0.22
Relative slag resistance:[g]													
Acid-steel slag	Good	Fair	Fair	Fair	Good	Good	Poor	Poor	Poor	Poor	Good	Good	Poor
Basic-steel slag	Poor	Poor	Poor	Poor	Fair	Fair	Good	Good	Good	Good	Good	Good	Poor
Mill scale	Fair	Poor	Fair	Good	Fair	Fair	Good	Good	Good	Good	Fair	Fair	Good
Coal-ash slag	Poor	Fair	Fair	Fair	Fair	Fair	Fair	Fair	Good	Good	Good	Good	Poor

[a] Made by hydraulic pressing.

[b] Includes CaO + MgO + alkalies.

[c] Pyrometric cone equivalent; terms "fusion," "softening," "deformation," and "melting points" heretofore loosely used.

[d] Data marked * are from A.S.T.M. test C 16-36 with high heat duty time-temperature schedule; those marked † are from same test with superduty time-temperature schedule; others determined by other commonly used tests.

[e] (+) means expansion; (−) means shrinkage.

[f] Oxidizing atmosphere.

[g] Ratings affected somewhat by varying temperatures and type of atmosphere prevailing. Resistance to coal-ash slag affected by furnace temperature as well as by analysis and fusion point of slag.

TABLE D-16.—VALUES FOR STRENGTH AND STIFFNESS OF AMERICAN BUILDING STONE

(Values based mainly on test data from the Watertown (Mass.) Arsenal)
(Moore, "Textbook of the Materials of Engineering," 6th ed., McGraw-Hill Book Company, Inc., New York, 1941)

Stone	Ultimate in compression, psi		Modulus of rupture (computed ultimate in cross bending), psi		Shearing strength, psi	Modulus of elasticity (flexure), psi	Weight (av), lb/cu ft
	Range	Av	Range	Av	Av	Av	
Granite.....	15,000–26,000	20,200	1,200–2,200	1,600	2,300	7,500,000	165
Marble.....	10,300–16,100	12,600	850–2,300	1,500	1,300	8,200,000	170
Limestone ..	3,200–20,000	9,000	250–2,700	1,200	1,400	8,400,000	160
Sandstone...	6,700–19,000	12,500	500–2,200	1,500	1,700	3,300,000	135
Slate.......	....	15,000	....	8,500	.....	14,000,000	175

TABLE D-17.—PHYSICAL PROPERTIES OF LOW-EXPANSION GLASSES, FUSED SILICA, AND FUSED QUARTZ

(Prepared from data given in *Chem. & Met. Eng.*, September, 1944)

	Borosilicate glass	96% silica glass	Fused quartz	Fused silica
Specific gravity........	2.23	2.18	2.20	2.07
Tensile strength, psi...	10,000	....	4,000	400–800
Thermal expansion, in./(1,000,000 in.)(°F)...	0.18	0.045	0.030	0.030
Thermal conductivity, Btu/(sq ft) (hr) (°F/ft).................	0.59	....	0.80	0.80
Specific heat, Btu/(lb)(°F)................	0.20	....	0.25	
Softening point, °F....	1,505	2,750 ± 90	2,600	2,600
Refractive index.......	1.47	1.458	1.459	
Transparency.........	Transparent or translucent	Transparent	Transparent	Translucent or opaque
Forms available:				
Sheets..............	Yes	...	Yes	Yes
Rods.......	Yes	Yes	Yes	Yes
Tubes..............	Yes	Yes	Yes	Yes
Other..............	Yes	Yes	Yes	Yes

TABLE D-18.—PHYSICAL PROPERTIES OF CHEMICAL STONEWARE
(Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York, 1941)

Specific gravity	2.2	Modulus of elasticity, psi	8×10^6
Hardness, scleroscope	100	Specific heat	0.2
Ultimate tensile strength, psi	2,000	Thermal conductivity, Btu/(hr)(sq ft)(°F/in.)	0.833
Ultimate compressive strength, psi	80,000	Linear thermal expansion per °F	2×10^{-6}
Modulus of rupture, psi	5,000	Water absorption, %	0–4

This table, which was prepared by the General Ceramics Co., gives the physical properties of an average grade of chemical stoneware. It should be emphasized here that "chemical stoneware" is not the name of a definite material, such as an alloy, but a generic term applied to a wide variety of ceramic compositions and hence that, in any particular composition designed to give optimum properties in one respect, it will ordinarily be impossible to secure optimum properties in all other respects.

b. Concrete.—The strength of even well-prepared concrete depends on age and on the proportion of water used in the mix. In general, low water contents yield higher strengths providing it is possible to compact the concrete so that the forms are completely filled. The proper choice of aggregate (sand, gravel, etc.) is important when high strength is required. Concrete should be kept moist during curing for development of full strength. Table D-19 gives data on strengths of concrete.

The 1940 report of the Joint Committee on Concrete and Reinforced Concrete has recommended working stresses of 25 per cent of ultimate compressive strength for concrete in compression. For concrete in flexure, they recommend that the extreme compression should not exceed 45 per cent of compressive strength and that the extreme tension should not exceed 3 per cent of the compressive strength. The bond between reinforcing and concrete should not be required to sustain stress exceeding either 160 psi or 4 per cent of compressive strength. For complete data on allowable stresses of all types the reader is referred to the original report.

The National Board of Fire Insurance Underwriters recommends a working stress for concrete in compression of 500 psi. This lower value should presumably be used for small jobs where the concrete may be poured and cured to loose specifications.

Most concrete structures of any consequence are reinforced with steel rods or netting. This reinforcing usually carries the bulk of the tension load because of the low tensile strength of concrete.

Concrete, though possessing a strong tendency toward porosity, may be made waterproof by proper attention to preparation, placing, and curing. Nonetheless, concrete tanks are sometimes waterproofed as an added precaution. Because of porosity, concrete may suffer some deterioration from freezing and thawing of moisture. The deterioration is likely to be serious for poorly prepared concrete.

The density of gravel concrete is roughly 150 lb/cu ft or 2 tons/cu yd. The exact density, of course, depends on the densities of the aggregates and the proportions used in the mix.

Table D-19.—Compressive and Tensile Strength, and Modulus of Elasticity of Concrete

(Moore, "Textbook of the Materials of Engineering," 6th ed., McGraw-Hill Book Company, Inc., New York, 1941)

Tests made at the Research Laboratory of the Portland Cement Association, Chicago. Compression tests of 6- by 12-in. and tension tests of 6- by 18-in. concrete cylinders.

Aggregate: Elgin sand and gravel graded 0 to 1½ in.; aggregate grading and consistency constant. Specimens removed from molds after one day and cured in moist room at 70°F until test; tested damp. Deformation of concrete measured with a Martens mirror extensometer.

Mix by volume	Cement, sacks per cu yd	Net water-cement ratio	Strength, psi						Initial tangent modulus of elasticity, 1,000 psi					
			3 days	7 days	28 days	3 mo	1 yr	5 yr	3 days	7 days	28 days	3 mo	1 yr	5 yr
Compression														
1–2	10.5	0.57	3,220	4,650	5,960	7,810	9,170	10,160	2,870	3,340	3,770	4,460	5,530	5,750
1–3	7.8	0.64	2,160	3,250	5,140	6,500	7,570	8,820	2,490	2,930	3,480	4,200	5,400	5,650
1–4	6.3	0.76	1,560	2,620	4,460	5,710	6,720	7,750	2,310	2,660	3,340	3,740	5,340	5,580
1–5	5.2	0.85	1,340	2,120	3,510	5,130	6,010	6,860	2,230	2,590	3,130	3,610	5,340	5,570
1–8	3.4	1.13	480	945	1,740	2,550	3,140	3,930	1,710	1,990	2,770	3,420	4,970	5,530
Tension														
1–2	10.5	0.57	325	360	460	525	630	635	2,770	3,200	4,050	4,450	5,500	5,550
1–3	7.8	0.64	230	290	400	480	595	590	2,770	3,130	3,840	4,050	5,250	5,600
1–4	6.3	0.76	175	240	360	415	525	565	2,700	3,000	3,560	4,150	5,470	5,380
1–5	5.2	0.85	130	225	325	390	510	520	2,420	2,780	3,200	3,630	5,160	5,300
1–8	3.4	1.13	40	85	185	270	335	350	2,210	2,700	3,030	3,410	4,840	4,700

c. Wood.—Table D-20 gives working stresses for woods. Table D-21 gives approximate densities of dry clear woods. The disadvantages of wood as a construction material are nonuniformity and swelling with water absorption. Recently the latter has been eliminated by impregnating wood with plastics.

TABLE D-20.—WORKING STRESSES FOR WOODS
(Stresses recommended by the U.S. Forest Service)

Species	Varied with conditions of exposure to moisture						Not varied with conditions of exposure	
	Continuously* dry		Occasionally wet but quickly dried		More or less continuously damp or wet			
	Extreme fiber stress in bending	Compression perpendicular to grain	Extreme fiber stress in bending	Compression perpendicular to grain	Extreme fiber stress in bending	Compression perpendicular to grain	Horizontal shear	Modulus of elasticity
Select grade†								
Cedar: Western red	900	200	710	150	670	125	80	1,000,000
Northern and south-white	750	175	580	140	530	100	70	800,000
Port Orford	1,100	250	890	200	800	150	90	1,200,000
Alaska	1,100	250	890	200	800	150	90	1,200,000
Cypress: Southern	1,300	350	980	250	800	225	100	1,200,000
Douglas fir:								
Coast region: Select	1,600	345	1,240	240	950	215	90	1,600,000
Dense select	1,750	380	1,370	265	1,050	235	105	1,600,000
Rocky Mountain region	1,100	275	800	225	620	200	85	1,200,000
Fir: Balsam	900	150	670	125	530	100	70	1,000,000
Golden, noble, silver, white	1,100	300	800	225	710	200	70	1,100,000
Hemlock: West coast	1,300	300	980	225	800	200	75	1,400,000
Eastern	1,100	300	800	225	710	200	70	1,100,000
Larch: Western	1,200	325	980	225	800	200	100	1,300,000
Oak: Red and white	1,400	500	1,070	375	890	300	125	1,500,000
Pine: Southern: Select	1,600	345	1,240	240	950	215	110	1,600,000
Dense select	1,750	380	1,350	265	1,040	235	128	1,600,000
California, Idaho, and northern white Pondosa and sugar	900	250	710	150	670	125	85	1,000,000
Norway	1,100	300	890	175	710	150	85	1,200,000
Redwood	1,200	250	890	150	710	125	70	1,200,000
Spruce: Red, white, Sitka	1,100	250	800	150	710	125	85	1,200,000
Engelmann	750	175	580	140	440	100	70	800,000
Tamarack: Eastern	1,200	300	980	225	800	200	95	1,300,000
Common grade								
Cedar: Western red	720	200	600	150	570	125	64	1,000,000
Northern and southern white	600	175	490	140	450	100	56	800,000
Port Orford	880	250	760	200	680	150	72	1,200,000
Alaska	880	250	760	200	680	150	72	1,200,000
Cypress: Southern	1,040	350	830	250	680	225	80	1,200,000
Douglas fir:								
Coast region	1,200	325	980	225	750	200	72	1,600,000
Rocky Mountain region	880	275	680	225	530	200	68	1,200,000

TABLE D-20.—WORKING STRESSES FOR WOODS (*Continued*)

Species	Varied with conditions of exposure to moisture						Not varied with conditions of exposure	
	Continuously* dry		Occasionally wet but quickly dried		More or less continuously damp or wet			
	Extreme fiber stress in bending	Compression perpendicular to grain	Extreme fiber stress in bending	Compression perpendicular to grain	Extreme fiber stress in bending	Compression perpendicular to grain	Horizontal shear	Modulus of elasticity
Common grade								
Fir: Balsam	720	150	570	125	450	100	56	1,000,000
Golden, noble, silver, white	880	300	680	225	600	200	56	1,100,000
Hemlock: West coast	1,040	300	830	225	680	200	60	1,400,000
Eastern	880	300	680	225	600	200	56	1,100,000
Larch: Western	960	325	830	225	680	200	80	1,300,000
Oak: Red and white	1,120	500	900	375	750	300	100	1,500,000
Pine: Southern	1,200	325	980	225	750	200	88	1,600,000
California, Idaho, and northern white Pondosa and sugar	720	250	600	150	570	125	68	1,000,000
Norway	880	300	760	175	600	150	68	1,200,000
Redwood	960	250	760	150	600	125	56	1,200,000
Spruce: Red, white, Sitka	880	250	680	150	600	125	68	1,200,000
Engelmann	600	175	490	140	370	100	56	800,000
Tamarack: Eastern	960	300	830	225	680	200	76	1,300,000

NOTE: For pieces of wood 5 in. or more in thickness for "occasionally wet" service slightly higher stresses are allowed for bending than given above for "occasionally wet" service.

* "Continuously dry" contemplates use in interior or protected construction not subjected to excessive dampness or high humidity.

"Occasionally wet but quickly dried" assumes use in such structures as bridges, trestles, grandstands or bleachers, and open sheds.

"More or less continuously damp or wet" applies to material exposed to waves or tidewater, or in contact with earth, or used in a building in portions likely to be continuously wet.

† "Select grade" and "common grade" are terms used to classify lumber according to the freedom from defects. The specifications for these two and other grades are given in the 1927 Proceedings of the American Railway Engineering Association, and the 1939 Standards of the A.S.T.M., Part II. Common grades of lumber provide material having not less than 60 per cent of the strength of green clear wood; for select grade the figure is 75 per cent.

TABLE D-21.—DENSITIES OF WOODS; SMALL, CLEAR TEST SPECIMEN, DRY BASIS (Abstracted from Moore, "Textbook of the Materials of Engineering," McGraw-Hill Book Company, Inc., New York, 1941)

Wood	Density, Lb/Cu Ft
Redwood	22
Cedar	23
Norway and white pine	24
Douglas fir and hemlock	28
Cypress	29
Tamarack	31
Yellow pine and elm	34
Spruce and ash	39
Maple	43
Red oak	45
White oak and hickory	50

d. Plastics and Elastomers.—New developments in the field of plastics are so rapid that even experts on the subject would be unable to give a fully adequate discussion of their properties. Plastics are made from a wide variety of starting materials, and each of the different types exhibits a range in properties that may be controlled by the conditions of manufacture. When plastics are combined with fibrous materials to make laminated plastics, plastic treated woods, etc., the variety obtainable is increased enormously. Consequently, plastics are frequently "tailor-made" to secure properties most suited to the intended use. As tables of data on properties presented here and elsewhere are likely to be misleading, plastics should not be excluded from consideration solely on the basis of such information. For example, laminated plastics of strengths comparable to steel have been made and may even now be available to industry; yet it would be difficult to find these data without searching the literature. Much the same comment applies to elastomers (*i.e.*, rubbery materials).

Tables D-22 and D-24 give data on the properties of a few of the better known plastics; Table D-23 gives data on rubber and related materials.

TABLE D-22.—RANGE OF VALUES OF PROPERTIES OF COMMON PLASTICS
(Values from test results obtained in various laboratories)
(Moore, "Textbook of the Materials of Engineering," 6th ed., McGraw-Hill Book Company, Inc., New York, 1941)

The values given in this table are ranges of values for various classes of plastics. If for any particular plastic within a class, more precise values are desirable, it will be necessary to obtain reports of tests of that particular plastic. Moreover, an examination of the test results for one lot of specimens from cellulose acetate sheet shows how greatly the mechanical properties vary with speed of testing. Data were wanting for the effect of speed of testing and of long-continued steady stress on the properties of nearly all the plastics on the market at the time this table was compiled, and the user of plastics must make rather large allowances for effects of time under load and for speed of loading, as well as for relatively slight changes in temperature.

Class of plastic (molded)	Weight, lb/cu in.	Tensile strength, psi	Compressive strength,* psi	Modulus of elasticity, psi	Toughness (Izod test notched bar), ft-lb	Max. safe temp., °F
Phenolic resins:						
General-purpose	0.049–0.052	6,500– 8,500	15,000	880,000– 970,000	0.13–0.20	300
Shock-resistant	0.050	5,300– 8,500	to	1,000,000–1,500,000	0.23–2.7	240–300
Heat-resistant	0.060–0.070	4,500– 6,000	36,000	1,700,000–2,000,000	0.13–0.50	400–450
Urea	0.053–0.055	9,500–12,000	25,000–35,000	1,000,000–1,700,000	0.15–0.18	212
Polystyrene	0.039	5,500– 7,000	10,000–13,000	400,000– 600,000	0.20–0.60	150–170
Celluloid	0.05 –0.06	4,000–10,000	....	300,000	....	160–190
Cellulose acetate	0.045–0.051	2,500– 9,000	12,000–16,000	145,000– 260,000	0.7 –2.0	140–180
Casein plastics	0.050	7,600	....	300,000	0.05–1.0	†
Vinyl resins	0.043	8,000–10,000	10,000–12,000	350,000– 430,000	0.15–0.35	140–150
Acrylic resins	0.043	4,000– 6,000	10,000–15,000	....	....	160 195

* Cylindrical specimens with height approximately equal to diameter.

† Swells under moist heat.

TABLE D-23.—PHYSICAL PROPERTIES OF SYNTHETIC AND NATURAL RUBBERS
(*Chem. & Met. Eng.*, September, 1944)

Material	Specific gravity of base material	Tensile strength, psi	Hardness, shore durometer	Max. temp. for use, °F†	Effect of heat	Abrasion resistance	Effect of sunlight‡	Effect of aging	Machining qualities
Chemigum, oil-resistant....	1.0–1.5	800– 4,000	30–90	300	Stiffens	Excellent	Equal to rubber	Stiffens	Can be ground
Chemigum, tire...........	1.0–1.15	1,000– 4,000	50–65	450	Stiffens	Good	None	Better than rubber	
GR-I (Butyl).............	0.91	500– 3,000	15–90	250–300	Stiffens slightly	Excellent	None	Highly resistant	Can be ground
GR-M (Neoprene)........	1.25–1.30	1,000– 4,500	10–95	300	Stiffens slightly	Excellent	None	Highly resistant	Can be ground
GR-N (Perbunan)........	0.96	500– 5,000	30–90	300	Stiffens	Excellent	Slight	Highly resistant	Can be ground
GR-P (Thiokol FA).......	1.34	1,400	25–90	200	Hardens slightly	Fairly good	None	None	Excellent
GR-P (Thiokol ST).......	1.27	500– 2,000	30–90	250–300	Hardens slightly	Good	None	None	Excellent
GR-S (Buna S), hard......	0.94	4,000–11,000	70–95*	220	....	....	....	Highly resistant	Excellent
GR-S (Buna S), soft.......	0.94	500– 3,000	25–95	300	Stiffens	Excellent	Deteriorates	Highly resistant	Can be ground
Hycar OR-15, soft........	1.00	500– 4,000	20–95	300	Stiffens	Excellent	Slightly better than natural rubber	Highly resistant	Can be ground
Hy OR-25, soft...........	0.99	500– 3,000	20–95	300	Stiffens	Excellent	Slightly better than natural rubber	Highly resistant	Can be ground

TABLE D-23.—PHYSICAL PROPERTIES OF SYNTHETIC AND NATURAL RUBBERS (*Continued*)

Material	Specific gravity of base material	Tensile strength, psi	Hardness, shore durometer	Max. temp. for use, °F†	Effect of heat	Abrasion resistance	Effect of sunlight‡	Effect of aging	Machining qualities
Hycar OR-15, hard	1.00	4,000–11,000	70–95	275	....	....	....	Highly resistant	Excellent
Hycar OS-10, soft	0.98	500– 3,500	20–95	300	Stiffens	Excellent	Deteriorates	Highly resistant	Can be ground
Koroseal, soft	1.40	500– 2,500	30–80	190	Softens	Good	None	Highly resistant	Can be ground
Koroseal, hard	1.40	2,000– 9,000	80–100	212	Softens	Excellent	None	Highly resistant	Good
Pliolite, No. 40	1.06	4,000– 5,000	......	160–248	Softens	....	None	None	
Resistoflex	1.26	2,000– 5,000	55–95	250	Softens	Good	None	None	
Tygon T	1.33–1.36	9,000	......	175	Softens	Good	None	....	Excellent
Vistanex, medium	0.9	200	......	......	....	....	None	Better than rubber	Cannot be machined
Vistanex, high	0.9	550	......	......	....	....	None	Better than rubber	Cannot be machined
Natural rubber, hard	0.93	4,000–11,000	70–95*	220	....	....	....	Highly resistant	Excellent
Natural rubber, soft	0.93	500– 5,000	20–95	300	Softens	Excellent	Deteriorates	Moderately resistant	Can be ground

* Type "D."

† Maximum temperature suitable for service depends greatly upon the exact service conditions. Maximum temperature for use as a packing can be much higher than the maximum temperature suitable for tank lining. Individual cases should be referred to the supplier for recommendations.

‡ Effect of exposure to sunlight under tension.

TABLE D-24.—LAMINATED PHENOLIC RESIN PLASTICS. STRENGTH VALUES AND USES

(Test results from various laboratories)

(Moore, "Textbook of the Materials of Engineering," 6th ed., McGraw-Hill Book Company, Inc., New York, 1941)

Base	Tensile strength, psi	Compressive* strength, psi	Uses
Paper	7,000–20,000	20,000–38,000	Bearings, electrical equipment
Fabric (usually canvas)	10,000–14,000	35,000–44,000	Gears, cams, bearings
Asbestos	9,000	30,000	High-temperature service†
Birchwood veneer with grain (plastic-bonded plywood)	30,000	23,000	Paneling, furniture

* Tests on 1-in.-cube specimens.

† Have been used in valves for live steam.

e. Carbon Products.

TABLE D-25.—PHYSICAL CHARACTERISTICS OF CARBON AND GRAPHITE PRODUCTS
(Abstracted from Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York, 1941)

Material and form	Apparent density	Weight, lb/cu ft	Strength, psi			Elastic modulus, psi (multiply by 10^5)	Specific resistance, ohms/in.^{3}	K (thermal expansion) (see Note)	Thermal conductivity, Btu/(hr)(sq ft)(°F/ft)
			Tensile	Compressive	Transverse				
Carbon tubes:									
½-4 in. ID	1.51	94.2	885	10,200	2,700	21.0	0.0014	15	3.0
5–10 in. ID	1.49	93.0	980	8,140	2,550	17.0	0.0016	21	3.0
Carbon brick:									
Dependent on application	1.56	96.7–97.8	970–1,530	5,340–8,320	1,950–3,070	8.9–10.3	0.0015–0.0016	13–14	3.0
Graphite tubes:									
½-4 in. ID	1.68	104.7	780	4,550	2,820	14.0	0.0003	12	94.0
5–10 in. ID	1.67	104.0	870	5,100	2,980	13.0	0.0003	12	84.0
Graphite brick, standard sizes	1.56	97.3	700	3,050	1,750	8.8	0.00036	5–12	84.0
Karbate No. 1 (impervious carbon):									
Tubes ½-2 in. ID	1.77	110.0	1,700	10,500	4,170	29.0	0.00164	27	3.0
Over 2 in. ID	1.76	110.0	2,000	10,500	4,640	26.0	0.0016	33	2.8
Karbate No. 2 (impervious graphite):									
Tubes ½-2 in. ID	1.86	116.0	2,600	8,900	4,650	23.0	0.00034	23	85.0
Over 2 in. ID	1.91	119.0	2,350	10,500	4,980	21.0	0.00033	24	75.0

NOTE: Coefficient of thermal expansion per degree: to temperature t°F = $[K + 0.0039t(°F)]\ 10^{-7}$; to temperature t°C = $[1.8K + 0.007t(°C)]10^{-7}$.

Carbon graphite products are resistant to most acids and alkalies.

4. Service of Materials Handling Process Fluids

a. General Notes on Corrosion.—Because corrosion and its twin, erosion, are extraordinarily complicated, no attempt will here be made to present detailed discussion. Rather a few of the complexities will be mentioned to forewarn the reader of the need of caution. *Inexperienced engineers are well advised to rely on advices of experts on corrosion.*

Corrosion may make itself known in several ways. The simplest is general surface attack, slowly reducing the thickness of the equipment. Instead of general surface attack, only isolated points may be affected, producing the familiar pitting. Microscopic examination of most materials of engineering shows them to be heterogeneous. The fluid may affect only certain of these component parts of the matrix. For example, in hydrogen and caustic embrittlements, only the intergranular material is attacked, but this may proceed until the cementing strength of this material is reduced and the metal becomes weak and brittle, even though unchanged in outward appearance. Failure of equipment may also result from other types of attack. For example, a plastic may absorb an organic solvent, swell, and deteriorate. Another example is the action of acetylene on copper. Though no appreciable attack is evident by inspection, enough copper carbide may form to cause an explosion and damage equipment.

Because process equipment generally handles moving rather than stagnant fluids, erosion is ordinarily associated with corrosion.

High stresses in metal usually increase corrosion rates. This is particularly true of "embrittlements," which rarely occur in unstressed metals. Conversely, corrosion affects the allowable stress and may reduce the endurance limit to zero.

Corrosion apparently proceeds by a wide variety of mechanisms. Of these one special case will be mentioned. When two metals are in contact with a solution containing even small amounts of electrolytes, an electric potential is set up between them which increases the rate of corrosion of the more basic (or electropositive metal). The increase may cause a more rapid corrosion rate than would occur by the use of either metal alone. In special cases, such as galvanized iron, the net rate of corrosion may be lowered. However, untried metal combinations should be avoided, particularly metals widely separated in the electrochemical series; for example, iron and copper should not be used together.

If corrosion is complicated, the lack of corrosion is simple. The best method of assuring this is choice of materials that are inert toward the fluids handled. Other expedients to reduce or prevent corrosion are

1. Protective paints.
2. Protective metal coatings (galvanizing, electroplating, liquid spraying, calorizing, etc.).
3. Protective films produced on surface by chemical reaction (pickling of steel, Parkerizing, etc.).
4. Control of pH of water solution. (Usually corrosion is at a minimum when slightly alkaline.)
5. Application of electric potential to equipment.

If a metal that is corroded by the material being handled must be used, then the equipment should be designed for low mechanical stresses and low velocities of flow so that corrosion will not be unduly increased either by stress corrosion or by erosion.

b. Metals.—Data presented in this section are reprinted from an article by L. G. Vande Bogart. In this reprinting, the liberty has been taken to convert his colors to numbers in order to simplify reproduction. For additional data on these and other metals see *Chem. & Met. Eng.*, **51,** No. 9, 107 (1945).

Table D-26 presents in visual form the results of a great deal of research and practical experience on the ability of some common metals and alloys to resist the corrosive effects of various liquids and gases. Such information is highly important in the selection of valves, fittings, and other equipment.

It should be kept in mind that these charts are indicative only. The recommendations are tentative and, when all the facts are known, the recommendations may change.

In general, No. 1 indicates that the corresponding metal and liquid or gas can be used together. However, some unexpected variable in a particular installation may veto such a recommendation.

No. 2 is a warning to proceed with caution. Usually it is meant to indicate that corrosion is to be expected, but that the rate will not be dangerously rapid. Again, it may indicate that a material will be satisfactory from the standpoint of probable life, but it is not suitable because even slight corrosion may be objectionable.

No. 3 indicates that a certain combination is not recommended, although there may be exceptions.

No notation indicates either a lack of data or a lack of necessity for using certain material. It does not necessarily forbid the corresponding metal-fluid combinations.

The terms "iron" and "steel" and "brass" refer to a group of alloys, rather than to any specific one.

TABLE D-26.—CORROSION RESISTANCE OF COMMON METALS AND ALLOYS

[L. G. Vande Bogart, Research Engineer, Crane Co., Chicago, Ill. Reprinted from *Factory Management and Maintenance*, **103**, No. 1, 145–148 (1945)]

KEY: 1. Can be and is being successfully used.
2. Proceed with caution. Used where corrosion is permissible; for temporary installations; where cost of better materials is too high, etc.
3. Should not be used.
Unnumbered: Information lacking.

	Iron and steel	Ni-resist. cast iron	18-8 Mo	Monel metal	Nickel	Red brass	Acid-resisting bronze	Aluminum
Acetate solvents, crude	2	2	2	1	1	2	1	1
Acetate solvents, pure	2	1	1	1	1	1	1	1
Acetic acid, crude	2	2	1	2	2	2	1	2
Acetic acid, pure	3	3	1	1	2	3	1	1
Acetic acid vapors[1]	3	3	1	2	..	2	3	2
Acetic anhydride	2	1	1	1	..	3	2	1
Acetone	1	1	1	1	1	1	1	1
Acetylene[2]	1	1	1	1	1	3	3	1
Alcohols	1	1	1	1	1	1	1	1
Aluminum sulphate alums	3	2	1	1	..	2	2	2
Ammonia gas[3]	1	1	1	1	1	3	3	1
Ammonium chloride	2	1	2	1	1	2	2	3
Ammonium hydroxide, ammonia liquors	1	1	1	2	2	3	3	1
Ammonium nitrate[4]	1	2	1	2	2	3	3	1
Ammonium phosphate (monobasic)	3	2	1	2	..	2	1	3
Ammonium phosphate (dibasic)	2	1	1	1	..	2	2	1
Ammonium phosphate (tribasic)	1	1	1	1	1	2	2	1
Ammonium sulphate	1	1	2	1	1	2	1	
Beer[5]	2	2	1	1	1	1	1	1
Beet sugar liquors	1	1	1	1	1	2	2	1
Benzene or benzol	1	1	1	1	1	1	1	1
Benzine	1	1	1	1	1	1	1	1
Borax	1	1	1	1	1	2	2	2
Boric acid	3	2	1	1	1	2	1	1
Butane, butylenes,[6] butadiene	1	1	1	2	2	1	1	1
Calcium bisulphite[7]	3	3	1	3	3	3	2	2
Calcium chloride[8]	1	1	2	1	1	1	1	3
Calcium hypochlorite	2	2	2	2	2	2	2	
Cane sugar liquors	1	1	1	1	1	1	1	1
Carbolic acid or phenol	2	2	1	1	1	2	2	1
Carbon dioxide, dry	1	1	1	1	1	1	1	1
Carbon dioxide, wet	2	2	1	1	1	2	2	1
Carbon disulphide	1	1	1	2	..	3	3	1
Carbonic acid, carbonated beverages	3	3	1	1	1	2	2	1
Carbon tetrachloride[9]	2	2	2	1	1	2	2	2
Chlorine, dry[10]	1	1	2	1	1	2	2	
Chlorine, wet[10]	3	3	3	3	3	3	3	3
Chromic acid[11]	2	2	1	2	2	3	2	2
Citric acid	3	2	1	1	1	2	1	1
Copper sulphate[12]	3	2	1	2	2	3	3	3
Core oils	1	..	..	..	..	1	1	
Cottonseed oil	1	1	1	1	1	2	1	

TABLE D-26.—CORROSION RESISTANCE OF COMMON METALS AND ALLOYS (*Continued*)

	Iron and steel	Ni-resist. cast iron	18-8 Mo	Monel metal	Nickel	Red brass	Acid-resisting bronze	Aluminum
Creosote, crude	1	1	1	1	1	2	1	1
Ethers	..	..	1	1	1	1	1	1
Ethylene glycol	1	1	1	1	1	1	1	1
Ferric chloride[11]	3	3	3	3	3	3	3	3
Ferric sulphate[12]	3	3	1	2	2	3	2	3
Formaldehyde	2	2	1	1	1	1	1	1
Formic acid	3	..	2	2	2	3	2	3
Freon, wet	2	1	2	1	1	1	1	1
Freon, dry	1	1	1	1	1	1	1	1
Furfural	1	..	..	1	1	1	1	1
Gasoline, sour	2	2	1	2	..	3	3	1
Gasoline, refined	1	1	1	1	..	1	1	1
Gelatine	..	..	1	1	1	3	2	1
Glucose	1	1	1	1	1	1	1	1
Glue	1	1	1	1	1	1	1	1
Glycerine or glycerol	1	1	1	1	1	1	1	1
Hydrochloric acid or muriatic acid[14]	3	3	3	2	2	3	2	3
Hydrofluoric acid[15]	2	3	3	2	2	3	2	3
Hydrogen gas[16]	1	1	1	1	1	1	1	1
Hydrogen peroxide	3	3	1	1	1	3	2	1
Hydrogen sulphide,[17] organic sulphur compounds	1	1	1	2	2	3	3	1
Lacquers and lacquer solvents	2	1	1	1	1	1	1	1
Lime-sulphur	1	1	1	1	1	3	3	
Magnesium chloride	2	2	2	1	1	2	1	3
Magnesium hydroxide	1	1	1	1	1	2	2	3
Magnesium sulphate	1	1	1	1	1	1	1	1
Mercury	1	1	1	1	1	3	3	3
Milk	3	3	1	2	1	3	3	1
Molasses	1	1	1	1	1	1	1	1
Nickel chloride[18]	..	..	2	2	2	3	3	3
Nickel sulphate[18]	..	..	2	2	2	2	2	3
Nitrating acids (water $<$ 20%, sulphuric $>$ 15%)	2	2	2	3	3	3	3	3
Nitrating acids (water $>$ 20%, sulphuric $<$ 15%)	3	3	2	3	3	3	3	3
Nitrating acids (water $>$ 20%, nitric $<$ 15%)	3	3	3	3	3	3	3	3
Nitrating acids (sulphuric + nitric = 1% or less)	3	2	1	3	3	3	3	1
Nitric acid, crude	3	..	2	3	3	3	3	2
Nitric acid, pure[19]	3	..	1	3	3	3	3	2
Oleic acid	2	2	1	1	..	2	1	1
Oxalic acid	2	2	..	1	..	2	1	1
Oxygen	1	..	1	1	..	1	1	1
Palmitic acid	2	2	1	1	..	2	1	1
Petroleum oils, not refined	1	1	2	..	..	2	2	
Petroleum oils, refined	1	1	1	1	1	1	1	1
Phosphoric acid, crude	2	..	2	2	2	3	3	3
Phosphoric acid, pure ($<$45%)	3	..	1	2	..	3	2	3
Phosphoric acid, pure ($<$45%, cold)	3	..	1	2	..	3	3	3
Phosphoric acid, pure[20] ($<$45%, hot)	3	..	2	2	3	3	3	3

TABLE D-26.—CORROSION RESISTANCE OF COMMON METALS AND ALLOYS (*Concluded*)

	Iron and steel	Ni-resist. cast iron	18-8 Mo	Monel metal	Nickel	Red brass	Acid-resisting bronze	Aluminum
Picric acid (aqueous solution)	2	..	1	3	3	3	3	1
Potassium chloride	1	1	2	1	1	1	1	2
Potassium hydroxide	2	1	2	1	1	3	3	3
Potassium sulphate	1	1	2	1	1	1	1	1
Propane gas[6]	1	1	1	1	1	1	1	1
Rosin, dark	1	1	1	1	1	2	1	1
Rosin, light	3	2	1	1	1	3	3	1
Shellac, orange	1	1	1	1	1	1	1	1
Shellac, bleached	3	2	1	1	1	2	2	1
Soda ash or sodium carbonate	1	1	1	1	1	2	2	3
Sodium bicarbonate or baking soda	2	1	1	1	1	2	1	2
Sodium bisulphate	3	2	2	1	1	2	1	2
Sodium chloride	1	1	2	1	1	1	1	2
Sodium cyanide	1	2	1	2	2	3	3	3
Sodium hydroxide	1	1	2	1	1	2	2	3
Sodium hypochlorite	3	2	2	2	2	3	3	3
Sodium metaphosphate	2	..	1	1	..	2	1	1
Sodium nitrate	1	1	1	1	1	2	2	1
Sodium perborate and sodium peroxide	2	1	1	1	1	2	2	1
Sodium phosphate (monobasic)	2	..	1	1	1	2	1	1
Sodium phosphate (dibasic)	2	1	1	1	1	1	1	1
Sodium phosphate (tribasic)	1	1	1	1	1	3	3	3
Sodium silicate	1	1	1	1	1	3	3	3
Sodium sulphate	1	1	2	1	1	1	1	
Sodium sulphide	1	1	1	1	1	3	3	3
Sodium thiosulphate or "hypo"	2	..	1	2	2	3	3	2
Stearic acid	2	2	1	1	1	2	2	1
Sulphate liquors[21]	1	1	1	1	..	3	3	3
Sulphur	1	2	2	2	2	3	3	1
Sulphur chloride	2	1	2	1	1	3	3	
Sulphur dioxide, dry[22]	1	1	1	1	..	1	1	1
Sulphur trioxide, dry[23,24]	1	1	1	1	..	1	1	1
Sulphuric acid[23] (98% to fuming)	1	1	2	3	3	3	3	2
Sulphuric acid (75–95%)[25]	1	..	3	3	3	3	3	3
Sulphuric acid (10–75%)[25]	3	2	3	1	2	3	2	3
Sulphuric acid (<10%)	3	2	2	1	2	2	1	3
Sulphurous acid	3	..	1	3	3	3	1	2
Tar	1	1	1	1	1	1	1	1
Tartaric acid	3	2	1	1	1	2	1	1
Toluene or toluol	1	..	..	1	..	1	1	1
Trichloroethylene[9]	2	2	2	1	1	2	2	
Turpentine	2	1	1	1	..	2	2	1
Varnish	2	2	1	1	1	2	2	1
Vegetable oils	1	1	1	1	1	1	1	1
Vinegar	2	2	1	1	1	2	2	2
Water, fresh (boiler feed, etc.)	1	1	..	1	1	1	1	2
Water, distilled[26] (laboratory grade)	3	3	1	2	1	3	3	1
Water, distilled (return condensate)	1	1	1	1	1	1	1	1
Water, salt (sea water, etc.)	2	1	2	1	2	1	1	2
Whiskey and wines	3	2	1	2	1	2	2	2
Zinc chloride	2	2	3	1	..	3	3	3
Zinc sulphate	2	1	..	1	..	2	2	

Reference Notes for Table D-26

1. Severe corrosion sometimes experienced at locations where liquid changes to vapor and vice versa.

2. Iron and steel used, but combinations that produce sparks should be avoided at valve seats. High-copper alloys prohibited by codes. Yellow brass acceptable.

3. These recommendations apply to industrial use of ammonia gas and to low-temperature stages of its manufacture. They do not all apply to the handling of hot gases in its manufacture by the synthetic process.

4. Iron and steel used. Some trouble experienced with hot solutions, especially adjacent to welds. Wherever possible, welds should be stress-relieved. Stainless steel first choice.

5. Iron and steel used for handling beer in the alcohol industry but not permissible in the beverage industry.

6. Recommendations do not apply to handling of these compounds at high temperatures. Behavior when hot depends largely on amount and nature of impurities. See Note 17, also Note 16.

7. Commonly encountered as pulping liquor in the pulp and paper industry. Copper and brass have been used in past and can be used again in emergency. Stainless steel (Type 316 or 317) preferred. Bronze valves should be trimmed with stainless steel.

8. Iron and steel used for refrigerating brines. Severe corrosion indicates need for control of solution.

9. These recommendations are based on industrial uses of the solvent. Galvanized steel commonly used for tanks, piping, etc. Iron and steel are widely used in manufacture of solvent, with good success.

10. Industrial applications of "dry" chlorine frequently involve locations where moisture is present. Steel gives good results as piping material but something better is needed for critical parts. Steel valves trimmed with monel or Hastelloy C give good results. Nonmetals required for wet gas and aqueous solutions.

11. Steel, with or without lead lining, used for tanks, piping, etc. Corrosion of unlined steel adjacent to welds is common. Wherever possible, welds should be stress-relieved if steel is not to be lined. Impingement by rapidly moving solution, especially when hot, may cause severe corrosion.

12. Presence of copper sulphate and/or ferric sulphate in dilute sulphuric acid inhibits the attack of this acid on stainless steel.

13. Nonmetals usually indicated. Hastelloy C used with some success.

14. Nonmetals usually indicated. Hastelloys used with excellent results. Hastelloy B used as trim in steel valves in hydrochloric alkylation. Red brass or bronze valves with nickel-alloy trim work well with dilute solutions (<1 per cent). Do not use Hastelloys with acid that has previously been in contact with copper alloys and has become contaminated with copper salts.

15. Steel standard for piping in hydrofluoric acid manufacture and in hydrofluoric alkylation. Steel valves should be trimmed with monel metal or Hastelloy B.

16. Recommendations apply to gas when used at ordinary temperatures. Extreme care should be exercised when the gas is to be handled at elevated temperatures, as in hydrogenation and dehydrogenation processes, etc.

17. Recommendations apply to dry gas at ordinary temperatures. Nickel alloys are very susceptible at elevated temperatures.

18. Commonly encountered as constituents of nickel-plating solutions, when equipment should be lead, lead-lined, Duriron, or rubber-lined.

19. Straight chromium alloys used in preference to chromium-nickel alloys when feasible to do so.

20. Special high chromium-nickel alloys required.

21. Includes black, green, and white liquors encountered in kraft paper mills. Iron and steel used for general piping. Low-nickel (1–2 per cent cast iron much superior to nickel-free cast iron and widely used for valve bodies, fittings, etc. Stainless steel used for valve trim. Evaporator tubes may require special alloys.

22. When gas is wet, apply recommendations for sulphurous acid.

23. When gas is wet, apply recommendations for sulphuric acid (<10 per cent).

24. Sulphur trioxide, either as a constituent of fuming sulphuric acid or when being handled as a gas, is capable of penetrating cast iron along the grain boundaries and causing intergranular cracking. Much cast-iron equipment is used, but safety considerations suggest that steel should be used wherever possible.

25. Special high chromium-nickel alloys having good resistance to a wide range of concentrations are being used. Ordinary iron and steel good where concentration remains over 90 per cent. Absorption of moisture from the air dilutes exposed acid and makes it more corrosive to iron.

26. Current practice in many cases where a mineral-free water is required is to use the effluent from a softener employing "hydrogen" zeolites. Such water may be distinctly "acid" and correspondingly corrosive. Final application may require that it be handled in rubber-lined pipe or in piping made of stainless steel, monel metal, etc.

c. Nonmetallics.—Ceramic stoneware, glass, and glass-lined equipment are frequently used because of their resistance to acids (except hydrofluoric) and oxidizing agents. Rubber-lined equipment is also employed for handling many acids (strongly oxidizing or anhydrous acids, however, may attack). Carbon products are resistant to most reagents and are frequently employed in heat exchangers in preference to other nonmetallics of lower thermal conductivity.

Woods present fair resistance to acid solutions, salts, and other reagents and are widely used in construction of tanks and large piping to take advantage of the relatively low cost.

Plastics are as yet not in wide use by the process industry. Their chief advantage so far appears to be for manufacture of small parts (such as bottle closures) to be used in contact with corrosive reagents. *Saran* pipe and tubing, cellulose-acetate tubing, and *Tygon* tubing have recently received favorable attention because of corrosion resistance and ease of handling. Data on resistance of a few plastics are given in Table D-27.

The use of plastics in conjunction with other materials, *i.e.*, for impregnating woods and as protective coatings for metals, will no doubt become of increasing importance.

TABLE D-27.—EFFECT ON PLASTICS OF IMMERSION FOR 7 DAYS IN CHEMICAL REAGENTS AT 25°C
(*Chem. & Met. Eng.*, September, 1944. From a paper, Resistance of Plastics to Chemical Reagents, by G. M. Kline, R. C. Rinker, and H. F. Meindl presented before Chicago meeting of A.S.T.M., June 24, 1941)

	Phenol-formal-dehyde molded	Phenol-formal-dehyde cast	Phenol-formal-dehyde lami-nated	Urea-formal-dehyde molded	Urea formal-dehyde lami-nated	Vinyl chloride-acetate resin	Vinyl butyral resin	Methyl metha-crylate resin	Styrene resin molded	Cellulose nitrate	Cellulose acetate	Ethyl-cellulose No. 1	Cold-molded phenolic	Casein plastic
30% sulphuric acid......	Surface roughened	None	Edges swollen	Surface roughened	Surface attacked	None	None	None	None	None	Crazed; softened	None	None	Rubbery
3% sulphuric acid.......	Surface roughened	None	Edges swollen	Surface roughened	Surface attacked	None	Cloudy	None	None	None	Swollen	None	None	Swollen; rubbery
10% nitric acid..........	Surface roughened	None	Edges swollen	Surface roughened	Delami-nated	None	Cloudy	None	None	None	Decom-posed	None	None	Swollen, cracked
10% hydrochloric acid...	Surface roughened	None	Edges swollen	Surface roughened	Delami-nated	None	Cloudy	None	None	None	Decom-posed	None	Cracked on drying	Swollen; cracked
5% acetic acid..........	None	None	Edges swollen	None	None	None	Cloudy	None	None	None	Swollen	None	None	Rubbery; split
Oleic acid..............	None	None	None	None	None	None	Tacky	None	None	None	None	Decom-posed	None	None
10% sodium hydroxide...	Decom-posed	Decom-posed	Delami-nated	None	Surface attacked	None	None	None	None	Crazed	Decom-posed	None	Decom-posed	Decom-posed
1% sodium hydroxide....	Surface roughened	Decom-posed	Edges swollen	None	None	None	Slightly cloudy	None	None	Crazed	Surface attacked	None	Decom-posed	Broken up
10% ammonium hydroxide	Surface dulled	Dis-colored	Dis-colored; edges swollen	None	None	None	Opaque	None	Dis-colored	Crazed; dis-colored	Opaque; soft	None	None	Swollen; split
2% sodium carbonate....	None	Dis-colored	Dis-colored	None	None	None	Slightly cloudy	None	None	None	Swollen	None	None	Swollen; rubbery
10% sodium chloride.....	None	None	Edges swollen	None	None	None	None	None	None	None	None	None	None	None

TABLE D-27.—EFFECT ON PLASTICS OF IMMERSION FOR 7 DAYS IN CHEMICAL REAGENTS AT 25°C (*Continued*)

	Phenol-formaldehyde molded	Phenol-formaldehyde cast	Phenol-formaldehyde laminated	Urea-formaldehyde molded	Urea formaldehyde laminated	Vinyl chloride-acetate resin	Vinyl butyral resin	Methyl methacrylate resin	Styrene resin molded	Cellulose nitrate	Cellulose acetate	Ethyl-cellulose No. 1	Cold-molded phenolic	Casein plastic
3% hydrogen peroxide...	None	Discolored	None	Surface dulled	Delaminated	None	Cloudy	None	None	None	None	None	None	Swollen; rubbery
Distilled water..........	None	None	None	None	None	None	Cloudy	None	None	None	None	None	None	Swollen; rubbery
50% ethyl alcohol.......	None	None	None	None	None	None	Swollen; rubbery	Slightly swollen	None	None	Partly dissolved	Swollen; cracked	None	Swollen; rubbery
95% ethyl alcohol.......	None	None	None	None	None	None	Dissolved	Surface attacked	None	Dissolved	Partly dissolved	Dissolved	None	None
Acetone................	None	Softened	Blistered	None	None	Dissolved	Swollen; opaque	Dissolved	Dissolved	Dissolved	Dissolved	Dissolved	None	None
Ethyl acetate...........	None	None	None	None	None	Decomposed	Decomposed	Dissolved	Dissolved	Dissolved	Dissolved	Dissolved	None	None
Ethylene chloride........	None	None	None	None	None	Dissolved	Decomposed	Dissolved	Dissolved	Partly dissolved	Soft; swollen	Dissolved	None	None
Carbon tetrachloride.....	None	None	None	None	None	None	Swollen; rubbery	Surface attacked	Dissolved	None	None	Dissolved	None	None
Toluene................	None	None	None	None	None	Soft; rubbery	Swollen; rubbery	Dissolved	Dissolved	Partly dissolved	None	Dissolved	None	None
Gasoline................	None	None	None	None	None	None	None	None	Partly dissolved	None	None	Swollen; cracked	None	None

d. Materials Used in Typical Services.

TABLE D-28.—MATERIALS OF CONSTRUCTION FOR CHEMICAL-ENGINEERING EQUIPMENT AS REPORTED BY TYPICAL USERS*
(*Chem. & Met. Eng.*, September, 1944)

	Acetic acid	Acetic anhydride	Alcohol	Aluminum chloride, anhydrous	Ammonia soda alkalies	Ammonium nitrate	Ammonium sulphate	Bromine
Absorbers	21, 5, 78, 28, 41	21	10		10			
Acetylators	21, 5, 78, 28, 41	3, 7, 28, 41, 78	21					
Agitators	21, 5, 78, 28, 41	3, 7, 28, 41, 78	9		10, 9	76		
Autoclaves	21, 5, 78, 28, 41	3, 7, 28, 41, 78						
Bins and hoppers			9	54, 9	20, 93, 10, 9	16, 68, 9		74
Centrifugals	21, 5, 78, 28, 41	3, 7, 28, 41, 78	7, 74		10, 74		7, 54	
Classifiers				54	10, 9			
Columns, fractionating	21, 5, 78, 28, 41	21, 3, 7, 28, 41, 78	21, 74		10, 9			33, 84
Condensers	21, 5, 78, 28, 41, 72	21, 3, 7, 28, 41, 78	21, 7, 2	9	10, 57, 54, 3			86, 33, 84
Condenser tubes	21, 5, 78, 28, 41, 72	21, 3, 7, 28, 41, 78	21	50L, 74, 9	10, 57, 54, 3			33, 86
Conveyers				54	69			
Cookers	21, 5, 78, 28, 41	21, 3, 7, 28, 41, 78	9					
Crushers and grinders			10	10, 54	10, 9			
Crystallizers	21, 5, 78, 28, 41		9		10, 9	10, 11		74
Driers	21, 5, 78, 28, 41	21, 3, 7, 28, 41, 78	10, 9		10, 9		42, 7	74
Drying towers	21, 5, 78, 28, 41				10, 9			
Evaporators	21, 5, 78, 28, 41	21, 3, 7, 28, 41, 78	21, 7		10, 57, 58	80, 76, 10		

* Numbers given indicate materials of construction as listed on p. 93.

Fans and blowers	21, 5, 78, 28, 41		9	54	10, 9			
Fermenters	23		93, 9, 23, 67					
Filter presses	21, 5, 78, 28, 41, 23	21, 3, 7, 28, 41, 78	10, 7, 54		10	10		74
Heat exchangers	21, 5, 78, 28, 41	21, 3, 7, 28, 41, 78	21, 9, 7	9	10, 3, 9	81, 80		57
Kettles	21, 5, 78, 28, 41	21, 3, 7, 28, 41, 78	21		10	10		
Piping	3, 21, 5, 78, 28, 41, 7, 74, 33, 33L	21, 3, 7, 28, 41, 78, 9	21, 74, 48, 9	9	10, 9	81,76, 9	6	33, 84, 50, 71
Pumps	21, 5, 78, 28, 41, 43	21, 3, 7, 28, 41, 78, 43, 10	10, 7, 54		10, 74, 54	10, 76	42, 94, 54	33, 84
Reaction vessels	21, 5, 78, 28, 41	21, 3, 7, 28, 41, 78			10, 9			74
Retorts	21, 5, 78, 28, 41	21, 3, 7, 28, 41, 78	10	29				
Screens	21, 5, 78, 28, 41		54, 7	54, 9	74	76, 9		
Scrubbers	21, 5, 78, 28, 41		10, 9		10			84
Shipping containers	93, 3, 33, 9, 93	3, 9	93, 61, 33, 9	9	47, 61, 93, 9, 57	66, 16, 68, 93, 9, 61		33, 50L, 84
Stills	21, 5, 78, 28, 41, 72L	21, 3, 7, 9, 28, 41, 78	21	9	10, 9			33, 86
Tanks, settling	21, 5, 78, 28, 41, 23	21, 3, 7, 9, 28, 41, 78	9		10, 9			
Tanks, storage	3, 21, 5, 78, 28, 41, 23, 84, 69L, 1	21, 3, 7, 28, 41, 78, 9	93, 9		10, 9	16, 68, 9, 10, 93		50L
Tanks, wash	21, 5, 78, 28, 41, 23		9		10, 20, 9			
Thickeners	21, 5, 78, 28, 41, 23				9			
Tower packing	64, 84	64, 84	84, 8		84, 8			64, 33, 84
Valves and fittings	3, 7, 21, 5, 78, 28, 41, 23, 15, 74	21, 3, 7, 28, 41, 84, 78, 9, 72L	10, 7, 54	9	10, 74, 54, 83	10, 76		33, 39, 84, 74

TABLE D-28.—MATERIALS OF CONSTRUCTION FOR CHEMICAL-ENGINEERING EQUIPMENT AS REPORTED BY TYPICAL USERS (*Continued*)

	Cane-sugar refining	Cellulose acetate	Chlorine, dry	Chlorine, wet	Chromic acid	Dyes	Ethyl acetate	Formaldehyde
Absorbers			84, 33L, 69L, 48, 9	84, 33L, 69L, 48		9, 10, 84, 40	30	
Acetylators		7, 21, 77, 57, 58				33L, 3	21, 74, 33L, 7, 50L	
Agitators	10, 6, 9		70, 33L, 39	70, 33L, 39	13	70, 51, 93, 39, 9, 10, 33L, 74, 50	21, 74	
Autoclaves						58, 9, 10, 13, 74		
Bins and hoppers	32, 74	3			9	58, 9, 74		
Centrifugals	7, 74	77, 7				70, 54, 7, 9, 74		
Classifiers	9							
Columns, fractionating	21		9			9, 10, 21, 74	21, 74	
Condensers	9, 21	74	9			9	21, 74	
Condenser tubes	21, 2		9			9, 2, 54	21, 74	
Conveyers	9, 7					9		
Cookers	9				9			
Crushers and grinders	9				13	10, 9, 74		
Crystallizers	9					10		
Driers	9	3	69L, 84, 33	69L, 84, 33		54, 9, 10, 74		
Drying towers			69L, 84, 33, 7	69L, 84, 33, 64, 71				
Evaporators	9, 10, 21		57, 9			9, 10		

Fans and blowers	9, 74		10, 9	84		9, 69L		
Fermenters	46							
Filter presses	10, 7, 50L, 54	93				93, 39, 10, 96		
Heat exchangers	9, 21, 2, 28		9, 57, 7	69L, 84, 33		33, 9, 10, 7	21, 74	
Kettles		77			9	9, 50L, 10, 1L, 3, 74, 69L, 33L		
Piping	9, 6, 21, 74	74, 21, 3	9, 21	69L, 33, 84	9	74, 93, 39, 69, 85, 71, 9, 10, 3, 69L, 50	21, 74, 53, 7	88
Pumps	10, 7, 74	74, 7, 42	10	43, 33		74, 10, 39, 69L, 7, 57, 36L	94, 74, 7, 53	74, 7
Reaction vessels	9	7, 74	33L, 57	33L, 57		74, 58, 23, 9, 50L, 10, 1L, 3, 33L	21, 74	
Retorts	74							
Screens	9, 7, 21, 54, 74					9, 6, 54, 74		
Scrubbers	9		84, 48	84, 48		9, 10, 84, 40		
Shipping containers	61, 22, 47, 9		9	9	9	61, 9, 93	53, 9	3
Stills	21					9, 74, 21	21, 74	
Tanks, settling	9					93, 9, 1L, 50L		
Tanks, storage	9, 21	74, 3, 93	9	9	9	74, 50L, 9, 3, 57, 69L	53	3, 74, 33L, 69L, 20
Tanks, wash						93, 9, 50L, 1L, 69L		
Thickeners	9							
Tower packing	64, 84		48, 84, 33	48, 84, 33		84, 8		
Valves and fittings	10, 7, 74	74	9, 54, 6, 57, 39, 10, 84, 48, 64	69	9	39, 54, 9, 10, 50, 6, 74, 57	7, 53	

TABLE D-28.—MATERIALS OF CONSTRUCTION FOR CHEMICAL-ENGINEERING EQUIPMENT AS REPORTED BY TYPICAL USERS (*Continued*)

	Formic acid	Glycerine	Hydrochloric acid	Hydrofluoric acid	Lactic acid	Magnesium chloride	Magnesium sulphate	Methylene chloride
Absorbers			85, 1, 48, 86, 40, 31, 15L, 84, 65L					
Acetylators								
Agitators	74				96	45	9, 54	
Autoclaves								
Bins and hoppers	9				74	9	9	
Centrifugals		28, 74, 54				45	9, 57	
Classifiers						45	9	
Columns, fractionating			48, 40, 85, 1, 65L					
Condensers	74	9	86, 48		74	9, 45	9	74, 18
Condenser tubes	74	21, 2, 54	86, 48		74	9, 45	9	
Conveyers						9, 10	9	
Cookers								
Crushers and grinders						9, 10		
Crystallizers						9, 69L, 1L	9, 54	
Driers						9, 45, 29L	9, 54	
Drying towers			1, 85L, 65L			9, 1L, 45		
Evaporators		10, 21, 9	48, 86, 1L, 65L		21, 74	9, 1L, 45	9, 74	
Fans and blowers			40, 91, 36L, 64, 84, 15			9	9	

Fermenters					96			
Filter presses		10, 32, 59	8, 34, 70			10, 59	10, 9, 93	
Heat exchangers			48, 86			9, 45, 59	9	
Kettles						1L, 74, 62L		
Piping	69L, 33L, 85, 74, 9, 33	9	91, 36, 71, 69L, 40, 33, 48, 64, 31, 84L	53, 71, 30, 21, 54, 57, 69	21, 74, 24, 72	9, 45	9	77
Pumps	43	10, 7, 74	68, 63, 48, 25, 33, 69L, 69, 36	53, 26, 36, 9, 54, 48	74, 7, 76	10, 59, 45	10, 54	74
Reaction vessels			85, 1, 48, 86, 40, 15L, 84, 65L					
Retorts								
Screens					74	9, 45	74, 54	
Scrubbers			85, 1, 48, 86, 40, 15L, 84, 65L		33, 40	93		
Shipping containers	33	9	69L, 33	9	93, 33	9	9	
Stills	10	9	48, 86, 1, 65L		74			
Tanks, settling					74	1L	9	
Tanks, storage	74, 40	3, 74, 54, 69L, 50L, 75L, 32	69L, 91, 40, 33, 84, 33L	53	74	9, 1L	9	77
Tanks, wash						1L	9	
Thickeners						45, 1L	9	
Tower packing			64, 8, 15			64		
Valves and fittings	26, 74, 43	9, 6	56, 69, 48, 54	53, 30, 54, 13	74, 72, 7, 69	10, 59	10, 74	

TABLE D-28.—MATERIALS OF CONSTRUCTION FOR CHEMICAL-ENGINEERING EQUIPMENT AS REPORTED BY TYPICAL USERS (*Continued*)

	Naphthalene	Nitric acid, strong	Nitric acid, weak	Paint and varnish	Phenol	Phosphoric acid	Potassium chloride	Potassium hydroxide
Absorbers		81, 80, 76, 1, 84	81, 80, 76, 1, 84					
Acetylators								
Agitators	9	76	76		77, 10, 9	70, 77, 50L, 1L	9, 10	57
Autoclaves	9							
Bins and hoppers	9					9	9	
Centrifugals	9, 74				74		54, 57, 45, 7	9, 57
Classifiers							9	
Columns, fractionating	9				9			
Condensers	9	43, 31, 33, 84	82, 81, 33, 43, 84, 31		21, 57, 1L, 9	10		57
Condenser tubes	9				17, 21, 57, 9, 77		54	57
Conveyers	9				9	69	9	
Cookers								
Crushers and grinders	9			9		69L, 50L, 9	9	
Crystallizers	9						9	57, 58
Driers					9		9	
Drying towers								
Evaporators	9	86, 43	86, 43		1L, 57, 10, 9, 77	50L, 1L, 78, 35, 51	10, 54, 9	57, 58
Fans and blowers	9				9	9, 70	9	

Fermenters								
Filter presses	9, 74					69, 77, 50, 93, 70	54, 9	10, 57
Heat exchangers	9	81, 76, 80	81, 76, 80		9, 74, 77, 7		54, 9	57
Kettles	9, 74, 54, 3			74, 33, 3	10, 50, 9			10
Piping	9, 50, 3	43, 3, 81, 33	81, 76, 80, 43, 33	74, 33, 32, 9	64, 33, 21, 9, 69L, 57, 10, 50	69L, 50L, 50, 69, 1L	69, 69L, 54, 10, 84, 93	9, 57
Pumps	9, 10, 50L, 43	43, 33, 74, 77, 84	77, 33, 43, 84	10	33, 38, 74, 50L, 9	77, 35, 70	59, 10	59
Reaction vessels	9				9, 10, 50L	70, 77, 50L, 1L		
Retorts	9							
Screens	74				77		76	57
Scrubbers	9	81, 84	81, 84		9	90, 21, 71, 54, 69		
Shipping containers	93, 47, 9	81, 80, 9, 3	81, 80, 9		9	9, 69L		9
Stills	9			74	9, 77			
Tanks, settling	9				9, 93	50L, 1L	9	9, 58
Tanks, storage	9, 3	33L, 4	81, 80, 33L		33L, 9	50L, 9	9	9
Tanks, wash	9				9		9	9
Thickeners						70, 93, 50, 77, 50L, 1L	9, 1L	9, 57, 58
Tower packing	84, 64	64, 84, 33, 1	1, 15, 33		64, 8, 15			
Valves and fittings	9	64, 43, 3, 81	43, 81	74, 9, 84, 43, 7	9, 10, 74, 50L, 64	77, 50L, 69L	10, 9, 74	57, 59

TABLE D-28.—MATERIALS OF CONSTRUCTION FOR CHEMICAL-ENGINEERING EQUIPMENT AS REPORTED BY TYPICAL USERS (*Concluded*)

	Soap	Sodium chloride	Sodium chromate and bichromate	Sodium hydroxide	Sodium hypochlorite	Sulphate pulp	Sulphide pulp	Sulphuric acid
Absorbers				9, 57, 54	69L		9	1, 84, 9
Acetylators								
Agitators	74, 54, 10, 7	77	9	9, 54, 57	69L, 72, 86			
Autoclaves			9					50L, 1, 10
Bins and hoppers	9, 58, 75	54, 93, 58	9	9, 54, 57			93, 9	9
Centrifugals		77, 54	9	9, 54, 57	69L, 77, 72			
Classifiers			9	9, 54, 57	69L	9		
Columns, fractionating								
Condensers			9	9, 57	69L	9		
Condenser tubes			9, 95	9, 2, 6	72, 33	74, 9		
Conveyers	9, 32	69, 54, 93	9	9, 54, 57		69	9, 69	
Cookers			9			53, 9, 78	1L	50, 53
Crushers and grinders			9, 10	10	69L			
Crystallizers		10, 74, 9	9, 10	9, 57	69L			
Driers	9	54, 54L, 95	9	10	10, 33L			1
Drying towers	9			84, 1				1L
Evaporators	21, 12, 10	10, 74, 21, 59, 9	9, 10	58, 10, 54, 57	69L, 72L	53		
Fans and blowers			9	9	69L	9, 78, 95, 54, 16	35	50L, 9, 10
Fermenters								
Filter presses	3, 21, 6, 7, 10, 9	59, 54	10	10, 9, 57	69L, 36, 92, 34			
Heat exchangers			9	57, 54, 9	72, 33			9, 74, 10
Kettles	58, 75, 9, 54L		9	10	33L, 72			

Piping	66, 9, 74	53, 9, 95	9, 10	9, 57, 15L, 69L	69L, 36, 10, 33, 72	9, 10, 95, 78, 36, 52	89, 93, 95, 10, 78, 21, 20L, 6	9, 10, 95, 50, 43, 40, 21, 7
Pumps	9, 74, 10, 54, 59, 7, 43	59, 94, 7	10, 7	57, 10, 43	69L, 43, 10	78, 77, 74. 59, 54, 27, 60, 7, 10, 12		10, 43, 74, 50, 94, 69L, 7, 35, 84, 33, 49, 44, 13
Reaction vessels			9	9, 10, 57, 69L	69L, 33L, 20			
Retorts								10
Screens		7, 74, 54	9	9, 54	77, 70, 72	54, 9, 74, 57	19	
Scrubbers			9	9, 10	84, 70			50, 84
Shipping containers	61	47, 61, 93	93, 61	9, 69L	33, 69L, 32, 9, 84			9, 50L, 33
Stills	74, 75, 54, 57							13
Tanks, settling	23, 9	67	9	9, 58, 57	69L, 20			
Tanks, storage	9, 23, 93, 75, 58	9	9	9, 58, 57	69L, 20		93	9, 33L, 84
Tanks, wash			9	9, 58	69L, 20	78, 54, 9, 10	93	
Thickeners			9	9	69L			
Tower packing			84, 64, 15	9	84, 64			1, 15, 33
Valves and fittings	9, 10, 74	7, 6	9, 10	10, 54, 57, 7	69L, 36, 10, 72, 37	78, 83, 54, 10, 77, 59, 14	50, 6, 7, 78, 54, 10	10, 50, 94, 39, 35, 43, 33L, 64, 69

L = Lined
1. Acidproof brick
2. Admiralty
3. Aluminum
4. Aluminum 2S
5. Aluminum bronze
6. Brass
7. Bronze
8. Carbon
9. Carbon steel
10. Cast iron
11. Cast iron (Ni, 2; Cr, 0.4)
12. Cast iron (Ni, 5)
13. Cast steel
14. Causul
15. Ceramics
16. Chlorinated rubber paint
17. Chrome alloy
18. Chrome steel
19. Chrome plate
20. Concrete
21. Copper
22. Cotton
23. Cypress
24. Dilecto
25. Durichlor
26. Duramet
27. Elcomet K
28. Everdur
29. Fire brick
30. Forged steel
31. Fused quartz or silica
32. Galvanized iron
33. Glass
34. Glass cloth
35. Hard lead
36. Hard rubber
37. Hastelloy
38. Hastelloy B
39. Hastelloy C
40. Haveg
41. Herculoy
42. High Cr steel
43. High Si iron
44. Illium
45. Inconel
46. Ingot iron
47. Jute
48. Karbate
49. LaBour-R55
50. Lead
51. Pb-covered Cu
52. Low Cr Ni C. I.
53. Mild steel
54. Monel
55. Natural rubber
56. Neoprene
57. Nickel
58. Nickel clad
59. Ni-resist
60. Ni steel (2%)
61. Paper
62. Phenolic resin
63. Plastic
64. Porcelain
65. Pyroflex
66. Red brass
67. Red wood
68. Resin-base paint
69. Rubber
70. Rubber-covered
71. Saran
72. Silver
73. Soapstone
74. Stainless
75. Stainless clad
76. Stainless 304
77. Stainless 316
78. Stainless 317
79. Stainless 344
80. Stainless 347
81. Stainless 430
82. Stainless 443
83. Stellite
84. Stoneware
85. Synthetic rubber
86. Tantalum
87. Tile
88. Tinned copper
89. Transite
90. Treated wood
91. Tygon
92. Vinyon
93. Wood
94. Worthite
95. Wrought iron
96. Yellow pine

CHAPTER E

THERMODYNAMIC DATA

Thermodynamics is the backbone of process engineering and, in fact, of a large portion of all engineering and physical science. Because of its importance there are available a large number of excellent texts on the subject, so that an exposition of the abstract principles of thermodynamics is neither necessary nor appropriate here. Below are listed a few of the more useful thermodynamic source books.

Chemical Thermodynamics:

Lewis and Randall, "Thermodynamics and the Free Energy of Chemical Substances," McGraw-Hill Book Company, Inc., New York, 1923.

Taylor and Glasstone, "A Treatise on Physical Chemistry," 3d ed., D. Van Nostrand Company, Inc., New York, 1942.

Steiner, "Introduction to Chemical Thermodynamics," McGraw-Hill Book Company, Inc., New York, 1941.

MacDougall, "Thermodynamics and Chemistry," 3d ed., John Wiley & Sons, Inc., New York, 1939.

Engineering Thermodynamics:

Weber, "Thermodynamics for Chemical Engineers," John Wiley & Sons, Inc., New York, 1939.

Lucke, "Engineering Thermodynamics," Columbia University Press, New York, 1941.

Goodenough, "Principles of Thermodynamics," 3d ed., Henry Holt and Company, Inc., New York, 1920.

Croft, "Thermodynamics, Fluid Flow and Heat Transmission," McGraw-Hill Book Company, Inc., New York, 1938.

Dodge, "Chemical Engineering Thermodynamics," McGraw-Hill Book Company, Inc., New York, 1944.

Thermodynamic Data:

"International Critical Tables," McGraw-Hill Book Company, Inc., New York.

Landolt-Börnstein, "Physikalisch-Chemischen Tabellen," 5th ed., Verlag Julius Springer, Berlin, 1936.

Bichowsky and Rossini, "Thermochemistry of the Chemical Substances," Reinhold Publishing Corporation, New York, 1936.

Parks and Huffman, "The Free Energies of Some Organic Compounds," Reinhold Publishing Corporation, New York, 1932.

Latimer, "Oxidation States of the Elements and Their Potentials in Aqueous Solution," Prentice-Hall, Inc., New York, 1938. (Free energy data.)

This chapter gives tabulations and charts of thermodynamic data which are useful for process calculation. At the end of the chapter some of the basic laws and equations of thermodynamics are given in the hope that they may prove useful to those versed in the subject without confusing others.

1. Equations of State

a. The Perfect Gas Law.—This law applies to all gases and vapors at very low pressures and may be applied further to most gases and vapors at moderate pressures without large error.

$$pV = RT \tag{E-1}$$

where p = pressure
V = volume
T = absolute temperature, °R or °K
R = gas-law constant (values in Table E-1)

TABLE E-1.—VALUES OF GAS-LAW CONSTANT, R
$pV = RT$

Units of				R
Pressure	Volume	Temperature	Quantity of gas	
Psi	Cu ft	°R = °F + 459.7	1 lb mole*	10.71
Psf	Cu ft	°R = °F + 459.7	1 lb mole	1,543
Psi	Cu ft	°R = °F + 459.7	1 SCF†	0.02838
Atm	Cu ft	°R = °F + 459.7	1 lb mole*	0.729
Atm	Cu cm	°K = °C + 273.16	1 g mole	82.06
Energy units				
Btu/(lb mole)(°R), or cal/(g mole)(°K)				1.9871
Btu/(SCF)(°F)				0.005247
Joule/(g mole)(°K)				8.3144

* The molecular weight expresses the number of pounds in a pound mole.

† One standard cubic foot (SCF) is the quantity of gas contained in 1 cu ft at 60°F and 30 in. of mercury (14.734 psi); 1 lb mole = 378.7 SCF. This is the definition used by the gas industry; it differs from that used by the *compressed* gas industry which defines the standard cubic foot at 70°F and atmospheric pressure (14.696 psi).

b. Reduced Equation of State.—A number of algebraic equations of state of varying degrees of accuracy and complexity have been developed. The most accurate of the simpler equations of state is the Dietrici equation:

$$p(V - b) = RTe^{-\frac{a}{RTV}} \tag{E-2}$$

The constants a and b appearing in this equation may be evaluated from the critical constants of the gas as follows:

$$a = 2RT_cV_c = \frac{4}{e^2}\frac{R^2T_c^2}{p_c} = \frac{R^2T_c^2}{1.846p_c}$$
$$b = \frac{V_c}{2} = \frac{RT_c}{e^2p_c} = \frac{RT_c}{7.389p_c}$$

where p = pressure
p_c = critical pressure, same units as p
V = volume
V_c = critical volume, same units as V
T = absolute temperature
T_c = critical temperature, same units as T
e = 2.7183, the base of the Napierian logarithms
R = gas constant (see Table E-1)

Equation (E-2) may also be expressed in the "reduced" form:

$$p_R(2V_R - 1) = T_Re^{\left(2-\frac{2}{T_RV_R}\right)} = 7.389T_Re^{-\frac{2}{T_RV_R}} \tag{E-3}$$

where $p_R = \frac{p}{p_c}$, the reduced pressure
$V_R = \frac{V}{V_c}$, the reduced volume
$T_R = \frac{T}{T_c}$, the reduced temperature

For most engineering purposes the reduced equation of state is more conveniently and accurately expressed in the following form:

$$pV = zRT \tag{E-4}$$

The factor z, called the "compressibility factor," expresses the deviation from the perfect gas law and is determined by the reduced pressures and temperatures. Figures E-1 to E-3 give numerical values of z. Figure E-1 is for vapors below the critical temperature; Fig. E-2 is for gases at or above the critical temperature and Fig. E-3 applies to the very high pressure range. Equation (E-4) may be employed with any units, provided the appropriate value of R is chosen.

To aid in the use of Eq. (E-4), the critical pressures and temperatures of a number of substances are given in Table E-2.

The reduced equation of state also forms the basis of correlations of latent heats, viscosities, and other physical properties.

TABLE E-2.—CRITICAL TEMPERATURES AND PRESSURES OF SOME COMMON SUBSTANCES

(Based mainly on data from "International Critical Tables" and from Matteson and Hanna, *Oil Gas J.*, May 21, 1942)

Substance	Temperature		Pressure
	°F	°R	Psi
Acetic acid, CH_3COOH	611	1071	841
Acetic anhydride, $(CH_3CO)_2O$	565	1025	676
Acetone, CH_3COCH_3	455	915	691
Acetylene, C_2H_2	96.8	556	911
Ammonia, NH_3	271.4	731	1,657
Aniline, $C_6H_5NH_2$	800	1260	770
Benzene, C_6H_6	551.3	1011	700
n-Butane, C_4H_{10}	305.6	765	551
n-Butyl alcohol, C_4H_9OH	549	1009	711
Carbon dioxide, CO_2	88.0	548	1,073
Carbon disulfide, CS_2	523	983	1,117
Carbon monoxide, CO	−218.2	241.5	514
Carbon tetrachloride, CCl_4	539.8	1000	661.5
Chlorine, Cl_2	291.2	751	1,119
Chlorobenzene, C_6H_5Cl	678	1138	656
Cyclohexane, C_6H_{12}	537.8	998	594
Ethane, C_2H_6	90.1	550	708
Ethyl acetate, $CH_3COOC_2H_5$	482.2	942	556
Ethyl alcohol, C_2H_5OH	469.6	929	927
Ethyl amine, $C_2H_5NH_2$	362	822	816
Ethylene, C_2H_4	49.5	509	749
Ethyl ether, $(C_2H_5)_2O$	381	841	522
n-Heptane, C_7H_{16}	512	972	397
n-Hexane, C_6H_{14}	454.6	914	434
Hydrazine, N_2H_4	716	1176	2,132
Hydrogen, H_2	−399.8	59.9	188
Hydrogen bromide, HBr	194.0	654	1,235
Hydrogen chloride, HCl	124.5	584	1,200
Hydrogen cyanide, HCN	362.3	822	735
Isobutane, C_4H_{10}	273.2	733	544
Isopentane, C_5H_{12}	370.0	830	482
Methane, CH_4	−116.5	343.2	673
Methyl acetate, CH_3COOCH_3	452.7	912	681
Methyl chloride, CH_3Cl	289.6	749	967
Methyl ether $(CH_3)_2O$	260.4	720	764
Nitrogen, N_2	−232.8	226.9	492
Nitrous oxide, N_2O	97.7	557	1,054
n-Octane, C_8H_{18}	564.8	1025	361
Oxygen, O_2	−181.8	277.9	731
Pentane, C_5H_{12}	387.0	847	485
Phenol, C_6H_5OH	786	1246	889
Propane, C_3H_8	206.2	666	617
n-Propyl alcohol, C_3H_7OH	506.7	966	734
Propylene, C_3H_6	196.8	656	668
Pyridine, C_5H_5N	651.2	1111	882
Sulphur dioxide, SO_2	315	775	1,142
Sulphur trioxide, SO_3	425.0	885	1,229
Toluene, $C_6H_5CH_3$	609.1	1069	611
Water, H_2O	705.4	1165	3,206

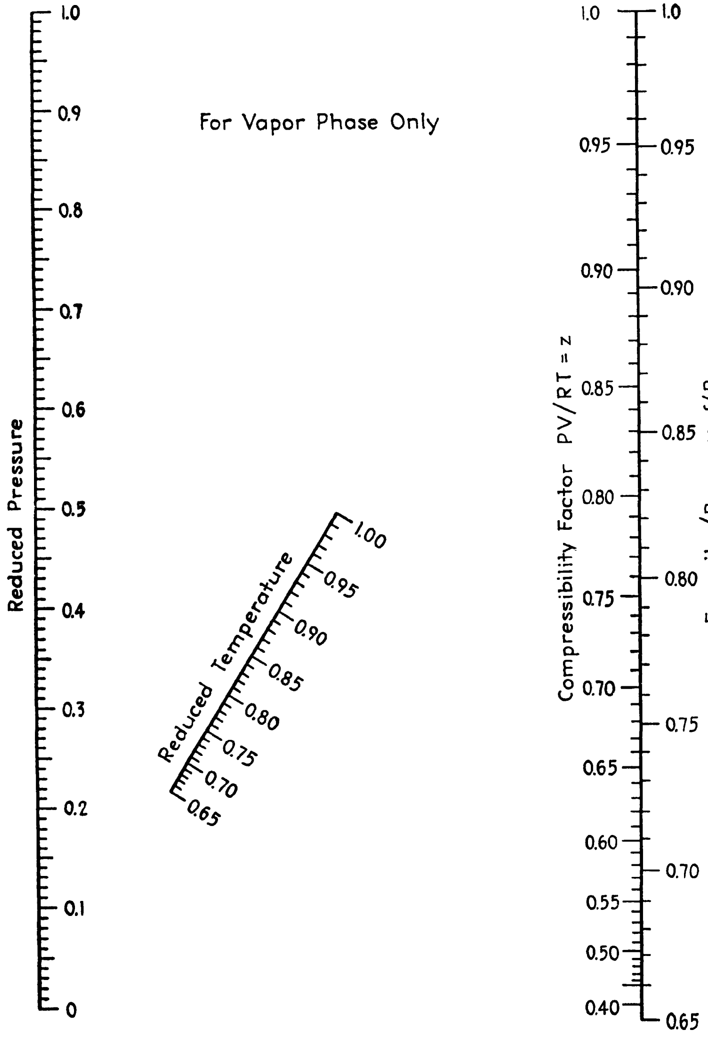


FIG. E-1.—Compressibility factors for vapors below the critical temperature. (*Thomson, Ind. Eng. Chem.* **35**, 895, (1943). *By permission of the American Chemical Society.*)

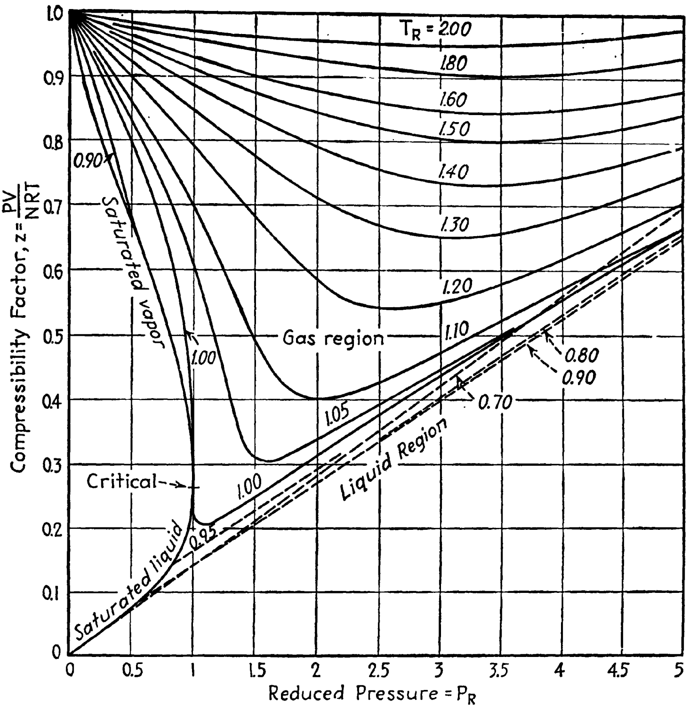


FIG. E-2.—Compressibility factors of gases. (*Reproduced by permission from "Thermodynamics for Chemical Engineers," by H. C. Weber, published by John Wiley & Sons, Inc., New York,* 1939.)

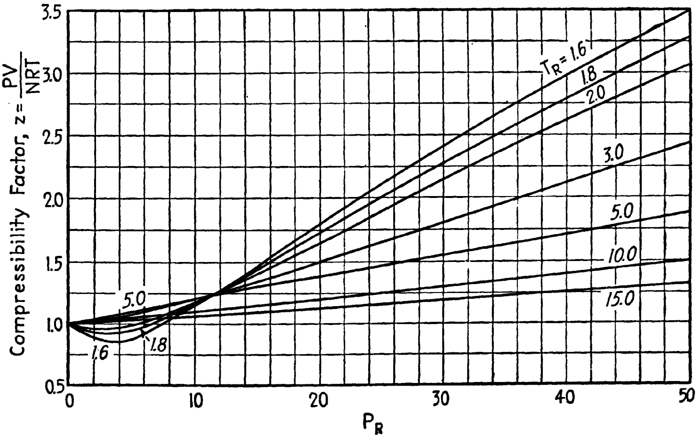


FIG. E-3.—Compressibility factors of gases at very high pressures. (*Reproduced by permission from "Thermodynamics for Chemical Engineers," by H. C. Weber, published by John Wiley & Sons, Inc., New York,* 1939.)

c. Gaseous Mixtures.—These may quite often be treated by either Dalton's law of additive pressures or by Amagat's law of additive volumes.

Dalton's law states that, in a mixture, each gas exerts the same (partial) pressure as if it alone occupied the volume and that the total pressure is the sum of the partial pressures of the individual components.

Amagat's law states that the volume occupied by a gaseous mixture is the sum of the volumes occupied by each component separately at the same temperature and pressure.

Both Dalton's law and Amagat's law are obeyed when the component gases all obey the perfect gas law. Although both fail for imperfect gases, Amagat's law is in the smaller error of the two.

Most imperfect gases may be treated with fair accuracy by the method of Kay.[1] He defines the pseudocritical pressure as the molal average of the individual critical pressures and the pseudocritical temperature as the molal average of the individual critical temperatures. Stating this in equation form,

$$p_c = N_1 p_{c1} + N_2 p_{c2} + \cdots \qquad \text{(E-5)}$$

$$T_c = N_1 T_{c1} + N_2 T_{c2} + \cdots \qquad \text{(E-6)}$$

where p_c = pseudocritical pressure
T_c = pseudocritical temperature
N_1 = mole fraction, component 1
N_2 = mole fraction, component 2, etc.
p_{c1} = critical pressure of component 1, etc.
T_{c1} = critical temperature of component 1, etc.

From these pseudocritical constants the reduced temperature and pressure may be computed for use in the reduced equation of state [Eq. (E-4)] as for a pure gas. This relation fails in the neighborhood of the critical point but is otherwise probably sufficiently accurate for engineering calculations.

d. Estimation of Liquid Densities.—Although the simple form of the reduced equation of state is not accurate when applied to the liquid state, the properties of liquids may be correlated by the use of the reduced temperatures and reduced pressures. Watson[2] discusses several such correlations.

Figure E-4 is a chart for estimating liquid densities of saturated

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[1] *Ind. Eng. Chem.*, **28**, 1014 (1936).

[2] *Ind. Eng. Chem.*, **35**, 398 (1943).

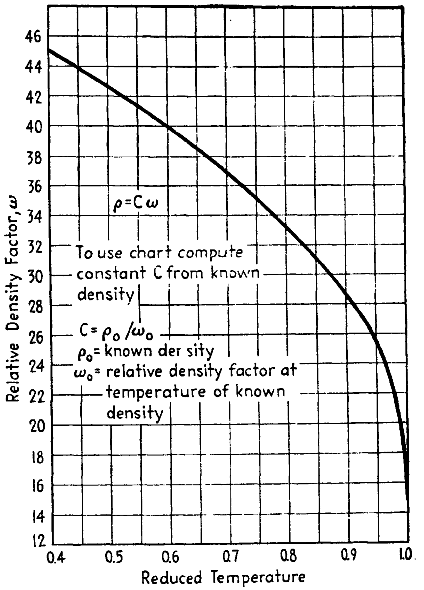


FIG. E-4.—Chart for estimating density of saturated liquids.

liquids (*i.e.*, under their own vapor pressures) from a single known density.

2. Specific Heats and Sensible Heats

a. Specific and Sensible Heats of Gases.—The heat capacities of a number of common gases are given in Fig. E-5. With the possible exception of acetylene, these values are believed to be reliable, provided the pressures are low. The heat capacities of hydrocarbons are based on the comprehensive tabulation of published data by Stull and Mayfield.[1] Values for bromine,[2] chlorine,[3] hydrogen sulphide,[4] steam,[5] and other gases[6] are taken from several sources.

[1] Stull and Mayfield, *Ind. Eng. Chem.*, **35**, 639 (1943).

[2] Gordon and Barnes, *J. Chem. Phys.*, **1**, 692 (1933).

[3] Spencer and Justice, *J. Am. Chem. Soc.*, **56**, 2311 (1934).

[4] Cross, *J. Chem. Phys.*, **3**, 825 (1935).

[5] Gordon, *J. Chem. Phys.*, **2**, 65 (1934). Keenan and Keyes, "Thermodynamic Properties of Steam," John Wiley & Sons, Inc., New York, 1936.

[6] Ellenwood, Kulik, and Gay, *Cornell Univ. Eng. Exp. Sta. Bull.* 30, 1942.

NOTE: Since preparation of the manuscript, considerable additional data on thermodynamics of hydrocarbons have been published. For example, see Pitzer, *Ind. Eng. Chem.*, **36**, 830 (1944), saturated hydrocarbons at atmospheric pressures; and Scheibel and Jenny, *Ind. Eng. Chem.*, **37**, 990 (1945), saturated hydrocarbons up to 1,000 psi.

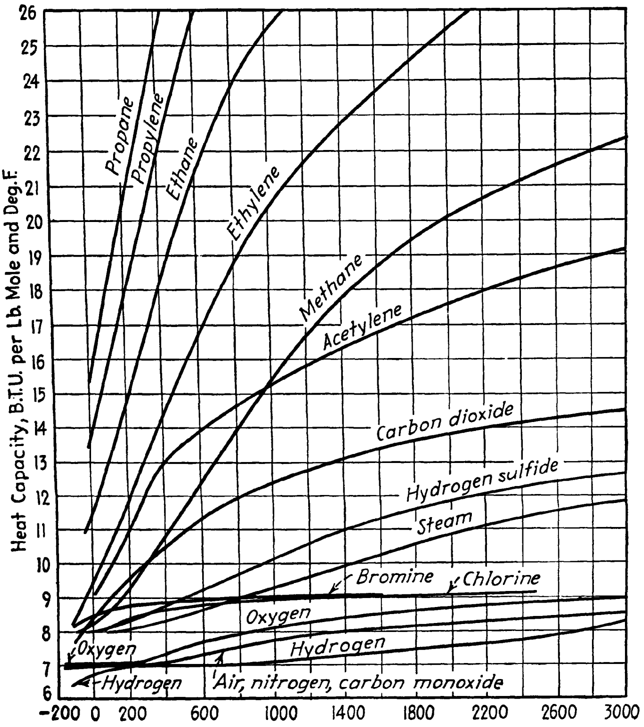


FIG. E-5.—Constant-pressure heat capacity of gases and vapors at low pressures.

Specific heat data may be summarized by empirical equations of the following type:

$$C_p = a + bT - cT^2 - \frac{d}{T^2} \qquad \text{(E-7)}$$

where C_p = specific heat or heat capacity

T = absolute temperature

$a, b, c, d,$ = empirical constants (usually one or more may be omitted)

Equations of this type are given for the constant-pressure heat capacities of a number of common gases in Table E-3.

The specific heat of a gas depends to some extent on the pressure. Figures E-6 to E-9 give the specific heats of air, hydrogen, carbon dioxide, and methane at various pressures. In the absence of specific data, the effect of pressure may be estimated by one or other of the following equations:

$$C_p = C_p^0 + 9\frac{p_R}{T_R^5} \quad \text{(when } T_R \text{ is less than 1.2)} \qquad \text{(E-8)}$$

$$C_p = C_p^0 + 5\frac{p_R}{T_R^2} \quad \text{(when } T_R \text{ is more than 1.2)} \qquad \text{(E-8a)}$$

where C_p^0 = heat capacity at low pressures, Btu/(lb mole)(°F)
C_p = heat capacity under pressure
$p_R = \frac{p}{p_c}$, the reduced pressure
$T_R = \frac{T}{T_c}$, the reduced temperature

TABLE E-3.—EMPIRICAL EQUATIONS FOR CONSTANT-PRESSURE HEAT CAPACITIES OF GASES AND VAPORS AT LOW PRESSURES

$$C_p = a + bT - cT^2 - \frac{d}{T^2}, \text{ Btu/(lb mole)(°F), where } T = \text{°R}$$

Substance	Molecular weight	*a*	*b*	*c*	*d*	Range, °R	References
Acetylene, C_2H_2	26.036	12.1	0.0025	....	1,000,000	500–2500	9
Ammonia, NH_3	17.032	7.12	0.00338	....	129,000	520–2500	4
Benzene, C_6H_6	78.108	6.16	0.0292	....	....	490–1000	7
n-Butane, C_4H_{10}	58.121	4.64	0.0310	....	....	490–1200	5
1-Butylene, C_4H_8	56.105	4.61	0.0285	....	....	490–1200	5
Bromine, Br_2	159.83	8.42	0.000541	0.11×10^{-6}	....	500–2500	1
Carbon dioxide, CO_2	44.010	10.34	0.00152	....	634,000	500–2500	2
Carbon monoxide, CO	28.010	6.60	0.00067	....	....	400–3000	2
Chlorine, Cl_2	70.914	7.58	0.00135	0.30×10^{-6}	....	500–2700	1
Ethane, C_2H_6	30.069	4.26	0.0158	....	....	490–1200	5
Ethylene, C_2H_4	28.052	3.08	0.0162	2.93×10^{-6}	....	500–2400	6
Hydrogen, H_2	2.016	6.62	0.00045	....	....	490–4500	2
Hydrogen bromide, HBr	80.92	6.80	0.00047	....	....	360–2600	2
Hydrogen chloride, HCl	36.46	6.73	0.00024	0.11×10^{-6}	....	500–3000	1
Hydrogen cyanide, HCN	27.02	10.13	0.00115	....	807,000	760–2700	4
Hydrogen sulphide, H_2S	34.076	7.15	0.00184	....	....	500–3000	2
Methane, CH_4	16.042	3.36	0.0100	1.30×10^{-6}	....	520–3600	8, 9
Nitric oxide, NO	30.008	8.05	0.00013	....	507,000	490–9000	2
Nitrogen, N_2	28.016	6.45	0.00080	0.025×10^{-6}	....	500–2800	1
Oxygen, O_2	32.000	6.10	0.0018	0.314×10^{-6}	....	500–3000	1
Propane, C_3H_8	44.095	4.16	0.0240	....	....	490–1200	5
Propylene, C_3H_6	42.079	4.00	0.0207	....	....	490–1200	5
n-Pentane, C_5H_{12}	72.147	5.16	0.0382	....	....	490–1200	5
Steam, H_2O	18.016	6.95	0.00180	0.100×10^{-6}	....	500–3500	9, 8
Sulphur dioxide, SO_2	64.06	11.4	0.000786	....	640,000	520–3500	3

1. Spencer and Justice, *J. Am. Chem. Soc.*, **56**, 2311 (1934); cf. Spencer, *J. Am. Chem. Soc.*, **67**, 1859 (1945).
2. Kelley, *U.S. Bur. Mines Bull.* 371 (1934).
3. Kelley, *U.S. Bur. Mines Bull.* 406 (1937).
4. Kelley, *U.S. Bur. Mines Bull.* 407 (1937).
5. Thacker, Folkins, and Miller, *Ind. Eng. Chem.*, **33**, 584 (1941).
6. Wenner, "Thermochemical Calculations," McGraw-Hill Book Company, Inc., New York 1941.
7. Edmister, *Ind. Eng. Chem.*, **30**, 352 (1940).
8. Bryant, *Ind. Eng. Chem.*, **25**, 820 (1933).
9. Privately derived.

Equation (E-8) is purely empirical but is sufficiently accurate for many purposes provided the correction for pressure is under 2.5 Btu/(lb mole)(°F). Equation (E-8*a*) is based on the Berthelot equation of state and may be used with a modest degree of accuracy provided the pressure correction is no more than 1 or 2 Btu/(lb mole)(°F).

The principal use of specific heats is for computing the heat change accompanying the heating or cooling of gases by the following relation:

$$Q = \Delta H = \int_{T_1}^{T_2} C_p\, dT$$
$$= a(T_2 - T_1) + \frac{b}{2}(T_2^2 - T_1^2) - \frac{c}{3}(T_2^3 - T_1^3) - d\left(\frac{1}{T_1} - \frac{1}{T_2}\right) \qquad \text{(E-9)}$$

where ΔH = increase in heat content of gas, Btu/lb or Btu/lb mole, etc.
Q = heat absorbed (at constant pressure)
T_1 = initial temperature, °R
T_2 = final temperature, °R
C_p = specific heat Btu/lb or Btu/lb mole, etc.
a, b, c, d = empirical constants, Eq. (E-7) (see Table E-3)

Often it is more convenient to compute the heat change from tabulations of heat contents usually referred to as sensible heats. Figures E-10 to E-12 (pp. 107, 108) give sensible heats of six gases; Fig. E-13 (p. 109) gives the sensible heats of the hydrocarbon gases. These charts are based on atmospheric pressure.

Heat contents (like specific heats) are dependent on pressure as well as temperature. Figure E-14 (p. 110) permits an approximate computation of the heat content under pressure from the low pressure values.

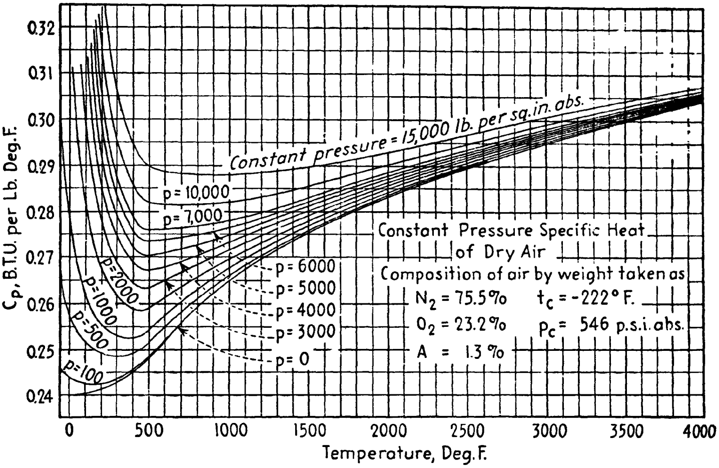


FIG. E-6.—The effect of temperature on C_p of air at various pressures. (*Ellenwood, Kulik, and Gay, "The Specific Heats of Certain Gases over wide Ranges of Pressures and Temperatures," Cornell Univ. Eng. Exp. Sta. Bull.* 30, 1942.)

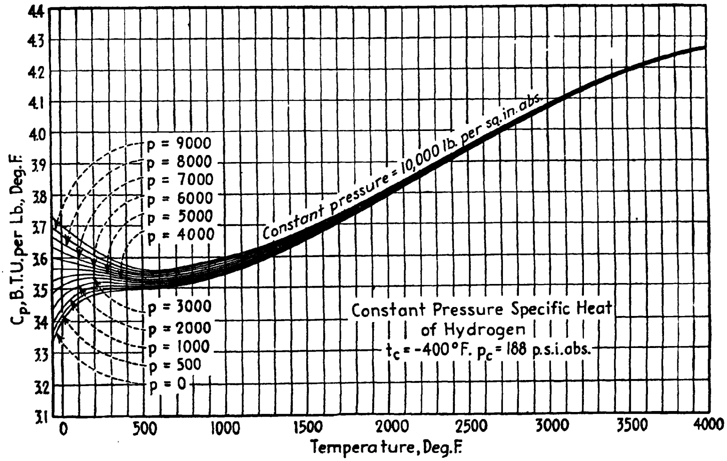


FIG. E-7.—The effect of temperature on C_p of hydrogen at various pressures. (*Ellenwood, Kulik, and Gay, "The Specific Heats of Certain Gases over wide Ranges of Pressures and Temperatures," Cornell Univ. Eng. Exp. Sta. Bull.* 30, 1942.)

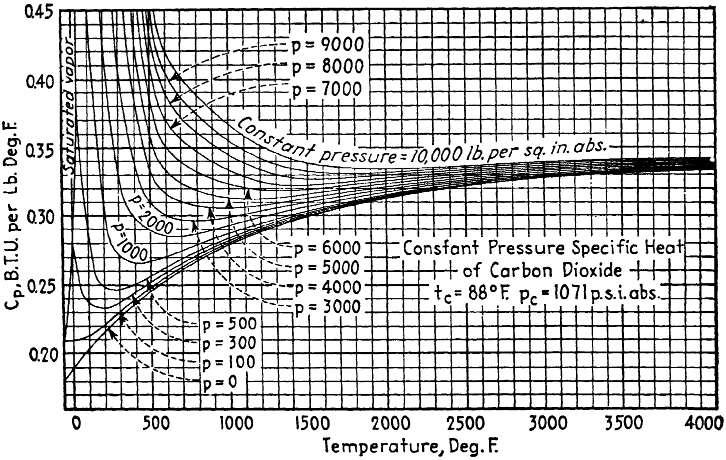


FIG. E-8.—The effect of temperature on C_p of carbon dioxide at various pressures. (*Ellenwood, Kulik, and Gay, "The Specific Heats of Certain Gases over wide Ranges of Pressures and Temperatures," Cornell Univ. Eng. Exp. Sta. Bull.* 30, 1942.)

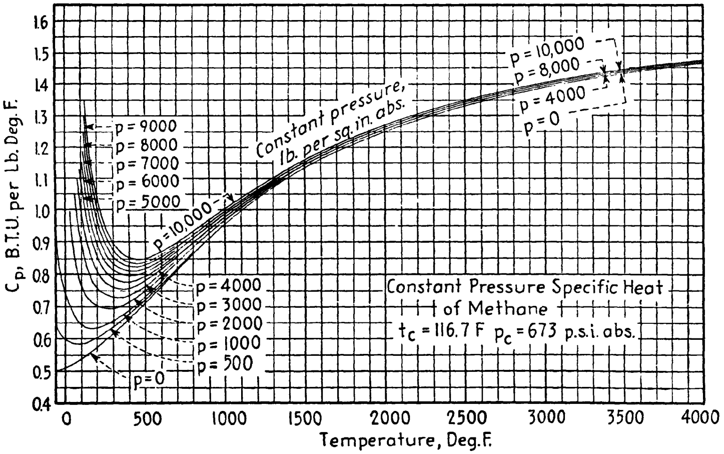


FIG. E-9.—The effect of temperature on C_p of methane at various pressures. (*Ellenwood, Kulik, and Gay, "The Specific Heats of Certain Gases over wide Ranges of Pressures and Temperatures," Cornell Univ. Eng. Exp. Sta. Bull.* 30, 1942.)

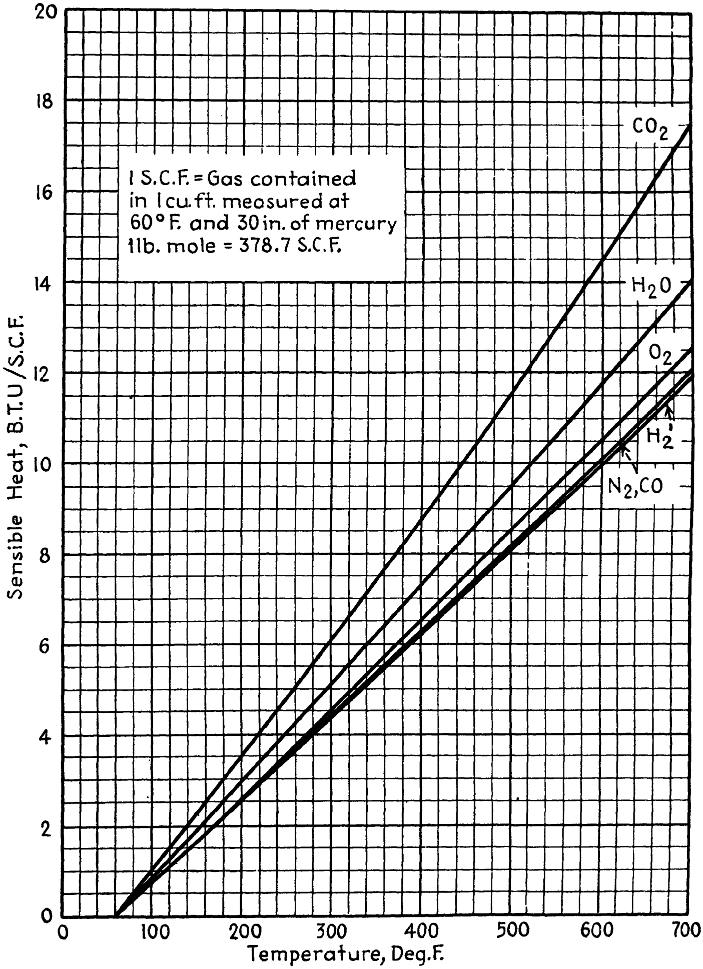


FIG. E-10.—Sensible heats above 60° F. Common gases at one atmosphere, low range.

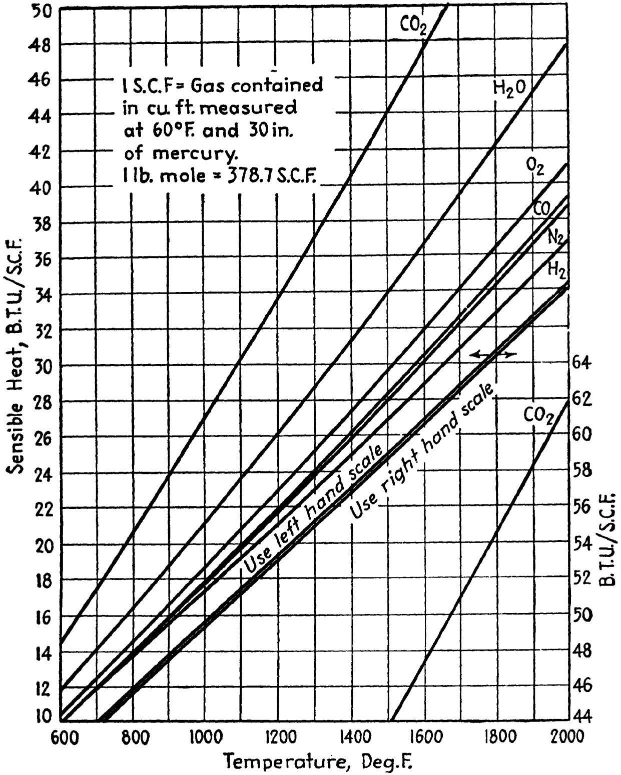


FIG. E-11.—Sensible heats above 60°F. Common gases at one atmosphere, middle range.

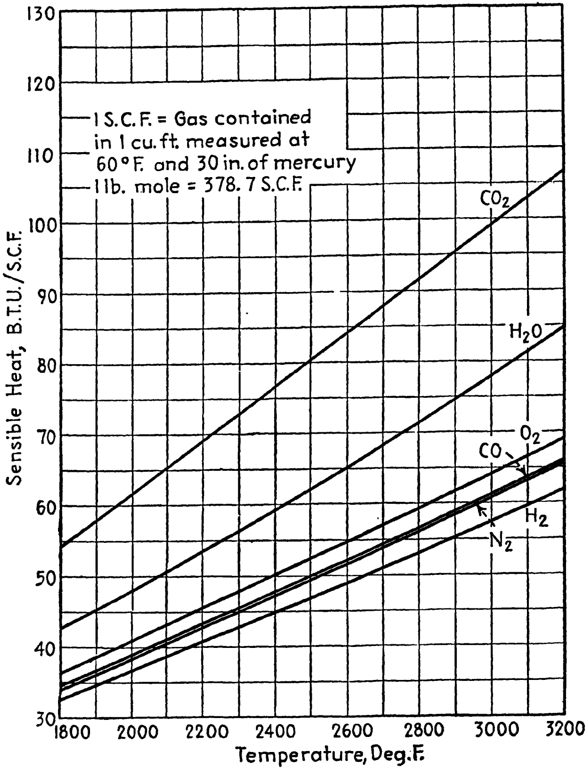


FIG. E-12.—Sensible heats above 60°F. Common gases at one atmosphere, high range.

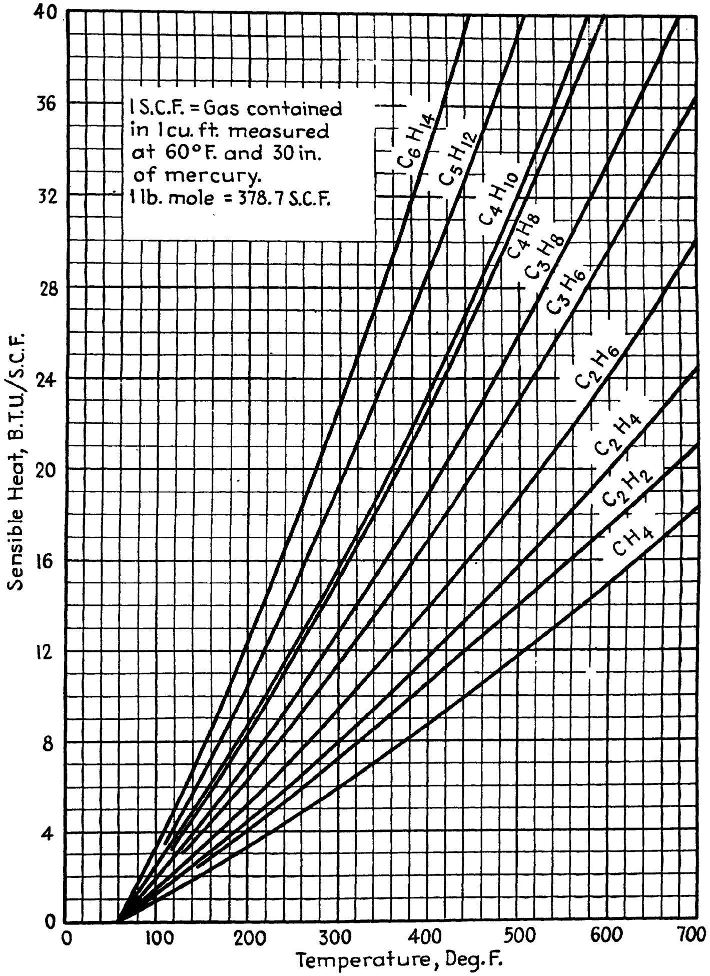
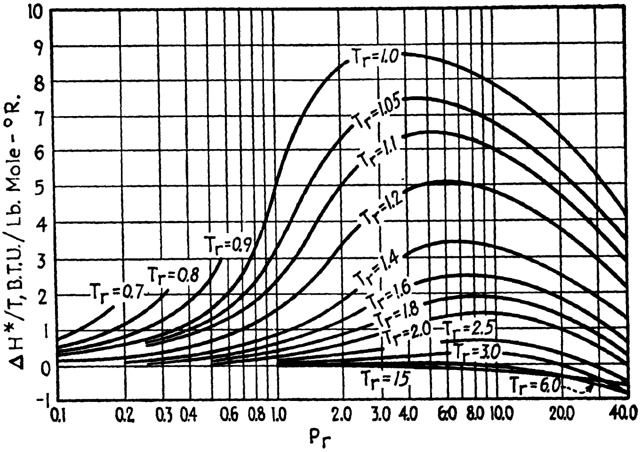


FIG. E-13.—Sensible heats above 60°F. Hydrocarbon gases at one atmosphere.

b. Specific Heats of Inorganic Solids and Liquids.—Table E-5 gives empirical equations for the specific heats of inorganic solids and liquids. As already discussed under gases, these equations may be integrated to obtain the heat effects.

$$Q = \Delta H = a(T_2 - T_1) + \frac{b}{2}(T_2^2 - T_1^2) - d\left(\frac{1}{T_1} - \frac{1}{T_2}\right) \quad \text{(E-9a)}$$



NOTE: To compute heat content under pressure subtract ΔH^* from heat content at low pressure.

FIG. E-14.—Enthalpy-pressure relationship for gases and vapors. (*Watson and Smith, "National Petroleum News," Technical Section, July,* 1936.)

Within the usual range of pressures, the specific heats and heat contents of solids and liquids are relatively constant, hence no correction need ordinarily be made for pressure effects.

Table E-4 gives sensible heats for a few inorganic solids.

TABLE E-4.—SENSIBLE HEATS ABOVE 60°F. INORGANIC SOLIDS
[Based on data of Kelley, *U.S. Bur. Mines Bull.* 371 (1934)]
Units, Btu/lb

	Temperature, °F												
	100	150	200	250	300	400	500	600	700	800	1000	1200	1500
Aluminum, Al	8	18	30	42	52	75	98	122	148	178	236	286	
Cadmium, Cd	2	5	8	10.5	13.5	19	25	31	61*	68*			
Calcium oxide, CaO	7	15	25	35	46	66	87	110	123	158	208	268	
Copper, Cu	3.5	8	13	18	23	32	41	51	61	72	95	116	150
Carborundum, SiC	7	16	26	36	46	67	89	114	139	167	220	278	365
Corundum, Al_2O_3	8	17	27	38	48	72	96	121	147	178	234	292	382
Graphite, C	8	18	29	40	52	79	107	138	171	215	283	370	506
Iron, Fe	4	10	16	21	27	39	51	65	80	97	130	168	224†
Lead, Pb	1	2.5	4	5.5	7	10	13	16	30*	33*			
Magnesium, Mg	10	22	34	47	60	86	112	141	169	200	264	322	
Salt, NaCl	8	18	29	40	51	72	94	116	138	164	216		
Fused silica, SiO_2	7	16	26	36	46	67	89	114	139	167	219	278	365
Zinc, Zn	4	8	13	18	23	33	43	53	64	75			

* Fused.

† β-iron.

TABLE E-5.—SPECIFIC HEATS OF INORGANIC SOLIDS AND LIQUIDS INCLUDING MOLECULAR WEIGHTS AND LATENT HEATS OF PHASE CHANGES

[Based on data of Kelley, *U.S. Bur. Mines Bull.* 371 (1934)]

$$c_p = a + bT - \frac{d}{T^2}, \text{ Btu/(lb)(°F)}$$

where a, b, d = constants given in this table
T = absolute temperature, °R

Substance*	Molecular weight	a	b	d	% error†	Absolute temp. range, °R	Enthalpy increase with phase change, Btu/lb
Aluminum:							
Al(s)	26.97	0.172	0.000066	......	1	490–1677	170 (fusion)
Al(l)	26.97	0.260	....	......	5	1677–3550	
Al_2O_3(s)	101.94	0.2166	0.0000489	16,600	3	490–2300	
$AlCl_3$(s)	133.25	0.0993	0.000117	......	3	490–838	
Mullite ($Al_6Si_2O_{13}$)	425.94	0.140	0.000874	......	5	490–1040	
Antimony:							
Sb(s)	121.76	0.0452	0.0000081	......	2	490–1626	70.5 (fusion)
Sb(l)	121.76	0.059	....	......	5	1626–2300	
Arsenic:							
As(s)	74.91	0.0690	0.0000174	......	5	490–2100	
As_2O_3(s)	197.82	0.042	0.000136	......	5	490–990	
Barium, $BaSO_4$(s)	233.42	0.09215	0.0000336	......	5	490–2380	
Beryllium, Be(s)	9.02	0.5208	0.000958	43,500	1	490–2100	
Bismuth, Bi(s)	209.00	0.0257	0.0000069	......	3	490–979	
Boron, B_2O_3(glass)	69.64	0.0738	0.000255	......	*ca.* 3	490–923	
Cadmium:							
Cd(s)	112.41	0.0486	0.000012	......	1	490–1069	23.4 (fusion)
Cd(l)	112.41	0.0634	....	......	5	1069–1750	
Calcium:							
CaO(s)	56.08	0.1783	0.000048	6,200	2	490–2100	
$CaCO_3$(s)	100.09	0.1966	0.000066	10,000	3	490–1860	
$CaSO_4$(s)	136.14	0.1360	0.0000897	3,730	5	490–2470	
$CaCl_2$(s)	110.99	0.152	0.000019	......	....	490–1900	
$Ca(OH)_2$(s)	74.10	0.289	....	......	....	500–670	
Carbon, C (graphite)	12.01	0.226	0.0001211	31,500	2	490–2470	
Chromium:							
Cr(s)	52.01	0.093	0.0000315	......	5	490–3281	136 (fusion)
Cr(l)	52.01	0.19	....	......	10	3281–3460	
Cobalt:							
Co(s)	58.94	0.0869	0.0000314	......	5	490–3173	112 (fusion)
Copper:							
Cu(s)	63.57	0.0856	0.0000128	......	1	490–2443	88 (fusion)
Cu(l)	63.57	0.118	....	......	3	2443–2830	
CuO(s)	79.57	0.1366	0.000025	6,130	2	490–1460	
$CuSO_4$(s)	159.63	0.151	....	......	....	508	
$CuSO_4 5H_2O$(s)	249.71	0.269	....	......	....	508	
Gold, Au(s)	197.2	0.00284	0.00000405	......	2	490–2460	27.6 (fusion)
Hydrogen, H_2O(l)	18.016	1.001	....	......	0.5	492–312	970 (vaporization)
Iron:							
Fe(α)	55.84	0.0740	0.0000634	......	3	490–1874	11.0 (α-β transition)
Fe(β)	55.84	0.1096	0.0000334	......	3	1874–2122	11.6 (β-γ transition)

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* (s) denotes solid state, (l) liquid. (α), (β), etc., denote different crystalline forms.

† If no percentage of error given, values are estimated or are of uncertain accuracy.

TABLE E-5.—SPECIFIC HEATS OF INORGANIC SOLIDS AND LIQUIDS INCLUDING MOLECULAR WEIGHTS AND LATENT HEATS OF PHASE CHANGES (*Continued*)

Substance*	Molecular weight	*a*	*b*	*d*	% error†	Absolute temp. range, °R	Enthalpy increase with phase change, Btu/lb
Iron—(Cont.)							
$Fe(\gamma)$	55.84	0.150	....	......	5	2122–3013	6.4 (γ-δ transition)
$Fe(\delta)$	55.84	0.18	....	......	5	3013–3245	113 (fusion)
$Fe_2O_3(s)$	159.68	0.1550	0.0000558	8,600	2	490–1970	
$Fe_3O_4(s)$	231.52	0.1778	0.0000452	13,700	2	490–1920	
$FeS_2(s)$	119.96	0.089	0.000062	......	....	490–1390	
$FeSO_4(s)$	151.90	0.145	....	......	....	527–670	
$FeSO_47H_2O(s)$	278.01	0.35	....	......	....	524–574	
Lead:							
$Pb(s)$	207.21	0.0278	0.0000054	......	2	490–1081	10.6 (fusion)
$Pb(l)$	207.21	0.033	....	......	5	1081–2290	
$PbO(s)$	223.21	0.0463	0.0000079	......	2	490–980	
$PbCl_2(s)$	278.12	0.0571	0.0000161	......	2	490–1388	36.5 (fusion)
$PbO_2(s)$	239.21	0.053	0.000018	......	....	490	
Magnesium:							
$Mg(s)$	24.32	0.255	0.0000304	9,030	1	490–1661	86 (fusion)
$Mg(l)$	24.32	0.30	....	......	10	1661–1890	
$MgO(s)$	40.32	0.2693	0.0000165	16,800	2	490–3730	
$MgCl_2(s)$	95.23	0.182	0.000023	......	....	490–1780	
$MgCl_26H_2O(s)$	203.33	0.38	....	......	....	526–616	
$Mg(OH)_2(s)$	58.34	0.48	....	......	....	520–575	
$MgSO_4(s)$	120.38	0.222	....	......	....	530–670	
Manganese:							
$Mn(\alpha)$	54.93	0.0685	0.0000755	......	5	490–1994	2.2 (α-β transition)
$Mn(\beta)$	54.93	0.0921	0.0000400	......	5	1994–2371	3.9 (β-γ transition)
$Mn(\gamma)$	54.93	0.087	0.00427	......	5	2371–2687	113 (fusion)
$Mn(l)$	54.93	0.20	....	......	10	2687–3000	
$MnSO_4(s)$	150.99	0.182	....	......	....	527–670	
Mercury, $Hg(l)$	200.61	0.0329	....	......	1	490–1134	
Nickel:							
$Ni(\alpha)$	58.69	0.0726	0.0000605	......	2	490–1127	2.8 (α-β transition)
$Ni(\beta)$	58.69	0.119	0.000086	......	5	1127–3105	129 (fusion)
$Ni(l)$	58.69	0.146	....	......	10	3105–3430	
$NiSO_4(s)$	154.74	0.216	....	......	....	527–670	
Nitrogen:							
$NH_4Cl(\alpha)$	53.50	0.183	0.00038	......	5	490–824	32 (α-β transition)
$NH_4Cl(\beta)$	53.50	0.093	0.00035	......	5	824–941	
$NH_4Br(s)$	97.96	0.232	....	......	....	490–590	
$NH_4I(s)$	144.96	0.123	....	......	....	490–590	
$NH_4NO_3(s)$	85.05	0.37	....	......	....	490–527	
$(NH_4)_2SO_4(s)$	132.14	0.39	....	......	....	495–950	
Phosphorous:							
P(yellow)	30.98	0.177	....	......	5	490–571	8.5 (fusion)
$P(l)$	30.98	0.21	....	......	10	571–672	
$P_4O_{10}(s)$	284.08	0.0554	0.000212	......	2	490–1136	112 (sublimation)
Platinum, $Pt(s)$	195.23	0.0303	0.0000033	......	1	490–3370	

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* (*s*) denotes solid state, (*l*) liquid. (α), (β), etc., denote different crystalline forms.

† If no percentage of error given, values are estimated or are of uncertain accuracy.

TABLE E-5.—SPECIFIC HEATS OF INORGANIC SOLIDS AND LIQUIDS INCLUDING MOLECULAR WEIGHTS AND LATENT HEATS OF PHASE CHANGES (*Concluded*)

Substance*	Molecular weight	*a*	*b*	*d*	% error†	Absolute temp. range, °R	Enthalpy increase with phase change, Btu/lb
Potassium:							
$KF(s)$	58.10	0.186	0.000027	......	....	490–2030	
$KCl(s)$	74.55	0.1466	0.000028	......	2	490–1877	154 (fusion)
$KBr(s)$	119.01	0.0965	0.0000168	......	2	490–977	
$KI(s)$	166.02	0.073	0.0000065	......	....	490–1720	
$KNO_3(\alpha)$	101.10	0.064	0.0003	......	10	490–722	25 (α-β transition)
$KNO_3(\beta)$	101.10	0.285	....	......	5	722–1010	51 (fusion)
$KNO_3(l)$	101.10	0.292	....	......	10	1010–1150	
$K_2CO_3(s)$	138.20	0.216	....	......	....	530–670	
$K_2SO_4(s)$	174 25	0.190	....	......	....	520–670	
Silicon:							
Glass (SiO_2)	60.06	0.213	0.0000413	16,300	3½	490–3550	
Quartz(α)(SiO_2)	60.06	0.1810	0.0000806	13,000	1	490–1526	
Silver:							
$Ag(s)$	107.88	0.0519	0.0000077	......	1	490–2221	45 (fusion)
$Ag(l)$	107.88	0.076	....	......	3	2221–2830	
$AgCl(s)$	143.34	0.067	0.000036	......	2	490–1310	40 (fusion)
$AgNO_3(\alpha)$	169.89	0.1108	0.0000524	......	2	490–779	
Sodium:							
$Na(s)$	23.00	0.218	0.000130	......	1½	490–668	49 (fusion)
$Na(l)$	23.00	0.326	....	......	2	668–810	
$NaF(s)$	42.00	0.248	0.000038	......	....	490–2270	
$NaCl(s)$	58 45	0.185	0.000040	......	2	490–1831	222 (fusion)
$NaCl(l)$	58 45	0.272	....	......	3	1831–2170	
$NaI(s)$	149.92	0.083	0.000006	......	....	490–1680	
$NaClO_3(s)$	106.45	0.089	0.000244	......	3	490–950	90 (fusion)
$NaNO_3(s)$	85.01	0.0536	0.00038	......	5	490–1049	80 (fusion)
$NaNO_3(l)$	85.01	0.438	....	......	10	1049–1265	
$Na_2SO_4(s)$	142.05	0.232	....	......	....	520–670	
Sulphur:							
S(rhombic)	32.06	0.113	0.000111	......	3	490–663	4.8 (transition: rhombic to monoclinic)
S(monoclinic)	32.06	0.137	0.000076	......	3	663–706	16 6 (fusion)
Tin:							
$Sn(s)$	118.70	0.0426	0.0000235	......	2	490–974	26 (fusion)
$Sn(l)$	118.70	0.056	....	......	10	974–2290	
Titanium:							
$TiO_2(s)$	79.90	0.148	0.0000525	1,700	3	490–1280	
Zinc:							
$Zn(s)$	65.38	0.0804	0.000023	......	1	490–1247	44 (fusion)
$Zn(l)$	65.38	0.116	0.0000047	......	3	1247–2020	
$ZnO(s)$	81.38	0.140	0.0000099	7,260	1	490–2830	
$ZnSO_4(s)$	161.44	0.173	....	......	....	525–670	

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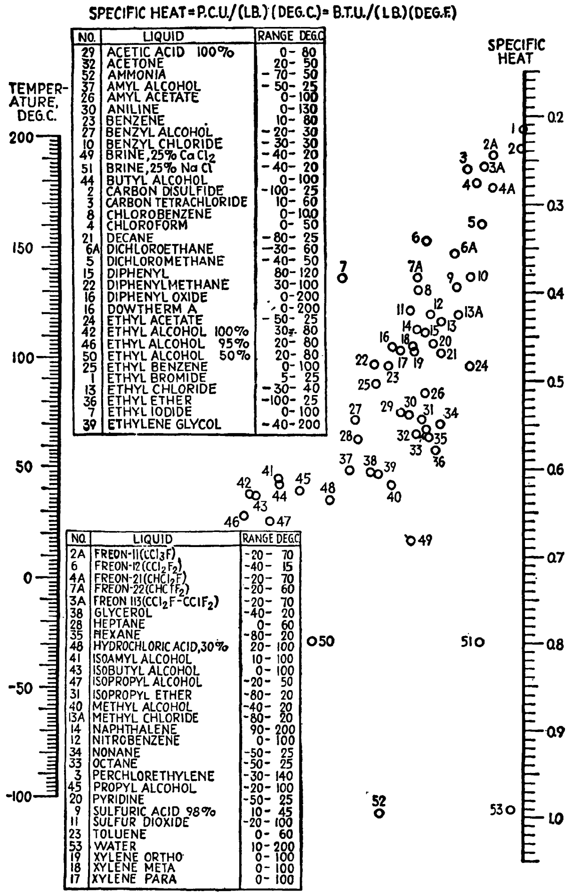
* (s) denotes solid state, (l) liquid. (α), (β), etc., denote different crystalline forms.

† If no percentage of error given, values are estimated or are of uncertain accuracy.



NO.	LIQUID	RANGE DEG.C
29	ACETIC ACID 100%	0- 80
32	ACETONE	20- 50
52	AMMONIA	- 70- 50
37	AMYL ALCOHOL	- 50- 25
26	AMYL ACETATE	0-100
30	ANILINE	0-130
23	BENZENE	10- 80
27	BENZYL ALCOHOL	- 20- 30
10	BENZYL CHLORIDE	- 30- 30
49	BRINE, 25% $CaCl_2$	- 40- 20
51	BRINE, 25% NaCl	- 40- 20
44	BUTYL ALCOHOL	0-100
2	CARBON DISULFIDE	-100- 25
3	CARBON TETRACHLORIDE	10- 60
8	CHLOROBENZENE	0-100
4	CHLOROFORM	0- 50
21	DECANE	- 80- 25
6A	DICHLOROETHANE	-30- 60
5	DICHLOROMETHANE	- 40- 50
15	DIPHENYL	80-120
22	DIPHENYLMETHANE	30-100
16	DIPHENYL OXIDE	0-200
16	DOWTHERM A	0-200
24	ETHYL ACETATE	- 50- 25
42	ETHYL ALCOHOL 100%	30- 80
46	ETHYL ALCOHOL 95%	20- 80
50	ETHYL ALCOHOL 50%	20- 80
25	ETHYL BENZENE	0-100
1	ETHYL BROMIDE	5- 25
13	ETHYL CHLORIDE	- 30- 40
36	ETHYL ETHER	-100- 25
7	ETHYL IODIDE	0-100
39	ETHYLENE GLYCOL	- 40- 200

NO.	LIQUID	RANGE DEG.C
2A	FREON-11 (CCl_3F)	-20- 70
6	FREON-12 (CCl_2F_2)	-40- 15
4A	FREON-21 ($CHCl_2F$)	-20- 70
7A	FREON-22 ($CHClF_2$)	-20- 60
3A	FREON 113 ($CCl_2F-CClF_2$)	-20- 70
38	GLYCEROL	-40- 20
28	HEPTANE	0- 60
35	HEXANE	-80- 20
48	HYDROCHLORIC ACID, 30%	20- 100
41	ISOAMYL ALCOHOL	10- 100
43	ISOBUTYL ALCOHOL	0- 100
47	ISOPROPYL ALCOHOL	-20- 50
31	ISOPROPYL ETHER	-80- 20
40	METHYL ALCOHOL	-40- 20
13A	METHYL CHLORIDE	-80- 20
14	NAPHTHALENE	90- 200
12	NITROBENZENE	0- 100
34	NONANE	-50- 25
33	OCTANE	-50- 25
3	PERCHLORETHYLENE	-30- 140
45	PROPYL ALCOHOL	-20- 100
20	PYRIDINE	-50- 25
9	SULFURIC ACID 98%	10- 45
11	SULFUR DIOXIDE	-20- 100
23	TOLUENE	0- 60
53	WATER	10- 200
19	XYLENE ORTHO	0- 100
18	XYLENE META	0- 100
17	XYLENE PARA	0- 100

FIG. E-15.—Specific heats of liquids. (*Chilton, Colburn, and Vernon, in Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York,* 1941.)

c. **Specific Heats of Organic Liquids.**—Figure E-15 gives the specific heats of a number of organic liquids. Table E-6 gives approximate specific heats of petroleum products. Table E-7 gives approximate heat contents of petroleum oils.

TABLE E-6.—SPECIFIC HEAT OF PETROLEUM OILS OF VARIOUS GRAVITIES IN BTU/(LB)(°F) OR CAL/(G)(°C)
[Reprinted from *Nat. Bur. Standards Misc. Pub.* 97 (1933)]

Temp., °F	Degrees A.P.I. at 60°F							
	10	20	30	40	50	60	70	80
	Specific gravity at 60°/60°F							
	1.000	0.9340	0.8762	0.8251	0.7796	0.7389	0.7022	0.6690
0	0.388	0.401	0.415	0.427	0.439	0.451	0.463	0.474
20	0.397	0.411	0.424	0.437	0.450	0.462	0.474	0.485
40	0.406	0.420	0.434	0.447	0.460	0.472	0.485	0.496
60	0.415	0.429	0.443	0.457	0.470	0.483	0.495	0.507
80	0.424	0.439	0.453	0.467	0.480	0.493	0.506	0.518
100	0.433	0.448	0.463	0.477	0.490	0.504	0.517	0.529
120	0.442	0.457	0.472	0.487	0.501	0.514	0.527	0.540
140	0.451	0.467	0.482	0.497	0.511	0.525	0.538	0.551
160	0.460	0.476	0.491	0.506	0.521	0.535	0.549	0.562
180	0.469	0.485	0.501	0.516	0.531	0.546	0.560	0.573
200	0.478	0.495	0.511	0.526	0.541	0.556	0.570	0.584
220	0.487	0.504	0.520	0.536	0.552	0.567	0.581	
240	0.496	0.513	0.530	0.546	0.562	0.577	0.592	
260	0.505	0.523	0.540	0.556	0.572	0.588	0.603	
280	0.514	0.532	0.549	0.566	0.582	0.598	0.613	
300	0.523	0.541	0.559	0.576	0.592	0.609	0.624	
320	0.532	0.550	0.568	0.586	0.603	0.619		
340	0.541	0.560	0.578	0.596	0.613	0.629		
360	0.550	0.569	0.588	0.606	0.623	0.640		
380	0.559	0.578	0.597	0.615	0.633	0.650		
400	0.568	0.588	0.607	0.625	0.643	0.661		
420	0.577	0.597	0.616	0.635	0.653			
440	0.586	0.606	0.626	0.645	0.664			
460	0.595	0.616	0.636	0.655	0.674			
480	0.604	0.625	0.645	0.665	0.684			
500	0.613	0.634	0.655	0.675	0.694			
520	0.622	0.644	0.665	0.685				
540	0.631	0.653	0.674	0.695				
560	0.640	0.662	0.684	0.705				
580	0.649	0.672	0.693	0.715				
600	0.658	0.681	0.703	0.724				
620	0.667	0.690	0.713					
640	0.676	0.699	0.722					
660	0.685	0.709	0.732					
680	0.694	0.718	0.741					
700	0.703	0.727	0.751					
720	0.712	0.737	0.761					
740	0.721	0.746	0.770					
760	0.730	0.755	0.780					
780	0.739	0.765	0.790					
800	0.748	0.774	0.799					

TABLE E-7.—HEAT CONTENT OF PETROLEUM LIQUIDS OF VARIOUS GRAVITIES IN BTU/GAL* ABOVE 32°F
[*Nat. Bur. Standards Misc. Pub.* 97 (1933)]

Temp., °F	Degrees A.P.I. at 60°F							
	10	20	30	40	50	60	70	80
	Specific gravity at 60°/60°F							
	1.000	0.9340	0.8762	0.8251	0.7796	0.7389	0.7022	0.6690
0	−105	−102	−99	−96	−93	−91	−88	−86
10	−73	−70	−68	−66	−64	−63	−61	−60
20	−40	−39	−37	−36	−35	−34	−34	−33
40	+27	+26	+25	+24	+24	+23	+23	+22
50	61	59	57	55	54	52	51	50
60	95	92	89	86	84	82	80	78
70	130	126	122	118	115	112	109	106
80	165	160	155	150	146	142	138	135
90	201	194	188	182	177	173	168	164
100	237	229	222	215	209	204	198	194
110	273	264	256	248	241	235	229	223
120	310	300	290	281	273	267	260	253
130	347	335	325	315	306	299	291	284
140	384	371	360	349	339	331	322	314
150	422	408	395	383	372	363	354	345
160	460	445	431	418	406	396	386	376
170	499	482	467	453	440	429	418	408
180	538	520	503	488	475	462	451	440
190	577	558	540	524	509	496	484	472
200	617	596	577	560	544	530	517	504
210	657	635	615	596	580	564	550	537
220	697	674	652	633	615	599	584	570
230	738	713	691	670	651	634	618	603
240	779	753	729	707	688	669	653	637
250	820	793	768	745	724	705	688	671
260	862	833	807	783	761	741	723	705
270	904	874	847	822	799	778	758	740
280	947	915	887	861	836	814	794	775
290	990	957	927	900	874	851	830	810
300	1034	999	968	939	913	889	866	846
310	1078	1041	1009	979	952	926	903	881
320	1122	1084	1050	1019	991	964	940	917
330	1166	1127	1092	1059	1030	1002	977	954
340	1211	1170	1134	1100	1070	1041	1015	981
350	1256	1214	1176	1141	1110	1080	1053	1028
360	1302	1258	1219	1183	1150	1119	1091	1065
370	1348	1303	1262	1225	1190	1159	1130	1103
380	1395	1348	1306	1267	1231	1199	1169	1141
390	1441	1393	1349	1309	1273	1239	1208	1179

* The unit used here is 1 gal of oil at 60°F.

TABLE E-7.—HEAT CONTENT OF PETROLEUM LIQUIDS OF VARIOUS GRAVITIES IN BTU/GAL* ABOVE 32°F (*Continued*)

Temp. °F	Degrees A.P.I. at 60°F							
	10	20	30	40	50	60	70	80
	Specific gravity at 60°/60°F							
	1.000	0.9340	0.8762	0.8251	0.7796	0.7389	0.7022	0.6690
400	1489	1439	1393	1352	1314	1280	1247	1217
410	1536	1485	1438	1395				
420	1584	1531	1483	1439				
430	1632	1578	1528	1483				
440	1681	1625	1573	1527				
450	1730	1672	1619	1571				
460	1779	1720	1666	1616				
470	1829	1768	1712	1661				
480	1879	1816	1759	1707				
490	1930	1865	1806	1753				
500	1981	1914	1854	1799				
510	2032	1964	1902	1846				
520	2084	2014	1950	1893				
530	2136	2064	1999	1940				
540	2188	2115	2048	1988				
550	2241	2166	2097	2036				
560	2294	2217	2147	2084				
570	2348	2269	2197	2133				
580	2402	2321	2248	2182				
590	2456	2373	2299	2231				
600	2511	2426	2350	2281				
610	2566	2479	2402	2331				
620	2621	2533	2454	2381				
630	2677	2587	2506	2432				
640	2733	2641	2558	2483				
650	2789	2696	2611	2534				
660	2846	2751	2665	2586				
670	2903	2806	2718	2638				
680	2961	2862	2772	2690				
690	3019	2918	2826	2743				
700	3078	2974	2881	2796				
710	3137	3031	2936	2849				
720	3196	3088	2991	2903				
730	3255	3146	3047	2957				
740	3315	3204	3103	3011				
750	3376	3262	3159	3066				
760	3436	3321	3216	3121				
770	3497	3380	3273	3177				
780	3559	3440	3331	3232				
790	3621	3499	3389	3289				
800	3683	3559	3447	3345				

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* The unit used here is 1 gal of oil at 60°F.

d. Specific Heats of Solutions.—Table E-10 gives data on specific heats of water solutions of a few inorganic compounds. Tables E-8 and E-9 give specific heats of aqueous methyl and ethyl alcohol, respectively.

TABLE E-8.—SPECIFIC HEAT OF METHYL ALCOHOL—WATER MIXTURES
BTU/(LB)(°F)
(Based on data from "International Critical Tables")

Weight % alcohol	40°F	60°F	80°F	100°F
0	1 005	1.000	0.999	0.999
10	1.025	1.005	1.00	0.995
20	0.97	0.98	0.98	0.98
30	0.92	0.945	0.95	0.95
40	0.87	0.91	0.915	0.92
50	0.82	0.855	0.87	0.975
60	0.77	0.805	0.82	0.83
70	0.72	0.75	0.77	0.78
80	0.67	0.70	0.715	0.725
90	0.62	0.645	0.665	0.675
100	0.57	0.595	0.615	0.625

TABLE E-9.—SPECIFIC HEAT OF ETHYL ALCOHOL—WATER MIXTURES, BTU/(LB)(°F)
(Based on data from "International Critical Tables")

Weight % alcohol	40°F	60°F	80°F	100°F
0	1.005	1.000	0.999	0.999
10	1.04	1.02	1.02	1.02
20	1.04	1.04	1 04	1.04
30	1.00	1.01	1.01	1.01
40	0.94	0.96	0.97	0.97
50	0.87	0.90	0.92	0.93
60	0.81	0.84	0.86	0.87
70	0.74	0.77	0.80	0.81
80	0.62	0.71	0.73	0.74
90	0.61	0.64	0.66	0.68
100	0.54	0.56	0.58	0.62

TABLE E-10.—SPECIFIC HEATS OF SOME WATER SOLUTIONS
(Data given in equation form based on data from "International Critical Tables")
P denotes weight %; T, absolute temperature, °R

Solution of	Specific heat, Btu/(lb)(°F)	Range	Accuracy, %
Hydrochloric acid, HCl	$C_p = 1 - 35\sqrt{P}/T$	40–140°F, 16–42%	4
Salt, NaCl	$C_p = 1 - 0.008P$	40–140°F, 0–25%	2
Ammonia, NH_3	$C_p = 1.0$	40–140°F, 0–40%	6
Sodium hydroxide, NaOH	$C_p = 1 - 0.032\sqrt{P}$	68°F, 0–57%	2
Potassium hydroxide, KOH	$C_p = 1 - 0.0115P$	66°F, 0–24%	2
Potassium chloride, KCl	$C_p = 1 - 0.0113P$	40–110°F, 0–31%	2

e. Specific Heats of Miscellaneous Materials.

TABLE E-11.—SPECIFIC HEATS OF MISCELLANEOUS MATERIALS
(Abstracted from Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York, 1941)

Material	Specific Heat, Btu/(lb)(°F)
Alumina	0.2(210°F); 0.274(2700°F)
Asbestos	0.25
Asphalt	0.22
Bakelite	0.3–0.4
Cellulose	0.32
Cement, portland clinker	0.186
Charcoal (wood)	0.242
Chrome brick	0.17
Clay	0.224
Coal	0.26–0.37
Coal tars	0.35(100°F); 0.45(390°F)
Coke	0.265(70–750°F) 0.36(70–1500°F) 0.40(70–2400°F)
Concrete	0.156(70–312°F); 0.219(72–1472°F)
Fire-clay brick	0.198(210°F); 0.298(2700°F)
Glass wool	0.16
Granite	0.20(70–210°F)
Limestone	0.22
Magnesite brick	0.222(210°F); 0.195(2700°F)
Sand	0.191
Steel	0.12
Wood (oak)	0.57
Most woods	0.45–0.65

3. Vapor Pressure

a. Vapor-pressure Charts.—Vapor pressures for a number of substances are summarized in Figs. E-16 to E-18. These charts, though

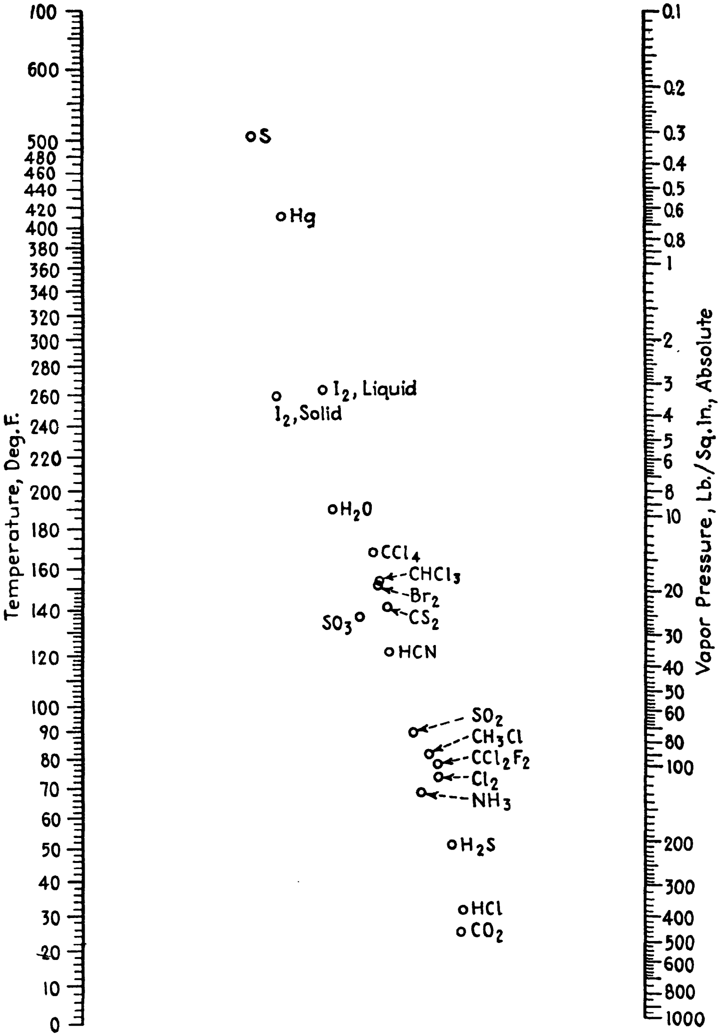

FIG. E-16.—Vapor pressures of inorganic compounds.

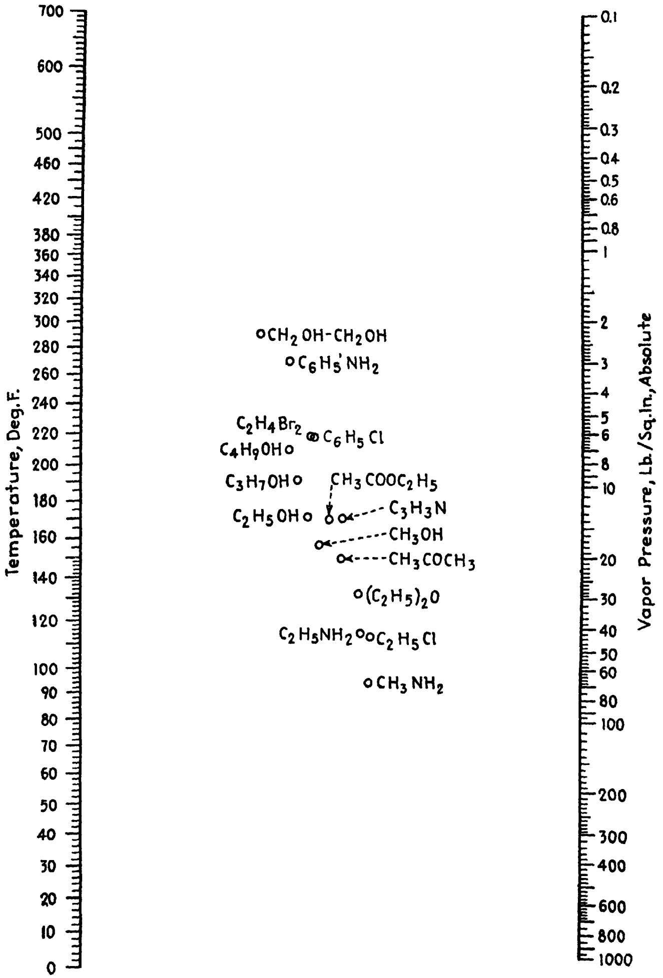

FIG. E-17.—Vapor pressures of organic compounds.

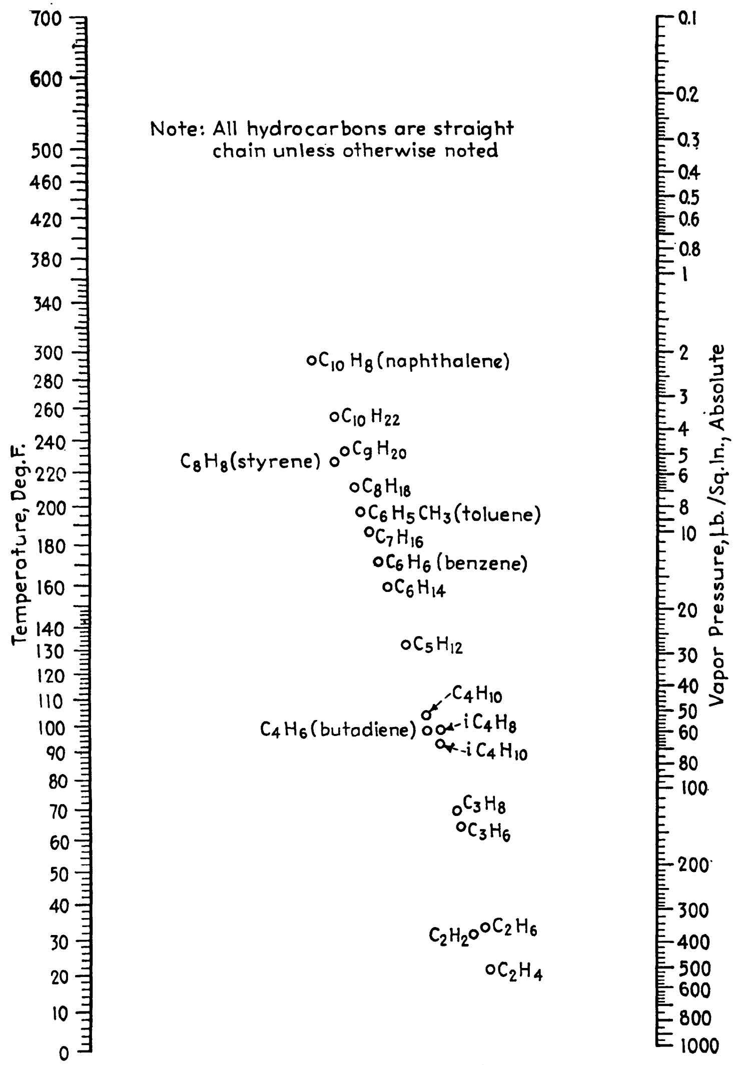

Fig. E-18.—Vapor pressures of hydrocarbons.

in nomograph form, are based on the familiar Cox[1] chart, using water as the reference liquid. The accuracy is about the same as the Cox relation in the conventional line plot. The basic data are taken from numerous sources.[2]

It will be noted at once that the vapor pressures may be extrapolated by these charts to above critical temperatures. Such values are, of course, fictitious and entirely devoid of physical reality except to permit a doubtful application of Raoult's law to solution of gases above the critical temperature.

The reader may readily add points for vapor pressures of other compounds to the charts, provided vapor pressures at two or more temperatures are available. To do this, draw lines each connecting an observed vapor pressure at the corresponding temperature. The intersection of these lines is the point representing the vapor pressure of the substance. Although valid for most pure liquids, the chart is not necessarily applicable to all liquid mixtures or to solids; further, it is not applicable to a very few substances like hydrogen fluoride and nitrogen dioxide which exhibit varying degrees of polymerization at different temperatures and pressures.

b. Other Correlations for Vapor Pressures.—The Clausius-Clapeyron equation in its integrated form is the most widely used method of correlating vapor pressures. This Eq. (E-10) assumes (1) that the latent heat of vaporization is constant, (2) that the vapor obeys the perfect gas law, and (3) that the volume of the liquid is much smaller than that of its vapor. These assumptions are all approximations.

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[1] *Ind. Eng. Chem.*, **15**, 592 (1923).

[2] Lange, "Handbook of Chemistry," Handbook Publishers, Sandusky, Ohio, 1939.

Hodgman, "Handbook of Chemistry and Physics," Chemical Rubber Publishing Co., Cleveland, Ohio, 1940.

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Wilson, Walker, Rinelli, and Mars, *Chem. Eng. News*, **21**, 1254 (1943).

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Gillespie and Fraser, *J. Am. Chem. Soc.*, **58**, 2260 (1936).

Sage and Lacey, *Ind. Eng. Chem.*, **34**, 730 (1942).

Kay, *Ind. Eng. Chem.*, **33**, 590 (1941).

Meyers and Van Dusen, *Nat. Bur. Standards J. Research*, **10**, 381 (1933).

Nat. Bur. Standards Circ. 142 (1923).

Keenan and Keyes, "Thermodynamic Properties of Steam," John Wiley & Sons, Inc., New York, 1936.

$$\log p = \frac{A}{T} + B \tag{E-10}$$

where p = vapor pressure, any convenient units
T = absolute temperature, °R or °K
A, B = empirical constants whose values depend on units of T and p

Values of A and B for a variety of substances are given in most handbooks and permit computation of vapor pressures with moderate accuracy, provided the pressure is not too high. An alternate form of this equation is

$$\log p_1 = \frac{\Delta H}{2.303R}\left(\frac{T_1 - T_2}{T_1 T_2}\right) + \log p_2 \tag{E-11}$$

where p_1 = vapor pressure at T_1, any units such as psi
p_2 = vapor pressure at T_2, same units as p_1
T_1, T_2 = absolute temperatures, °R or °K
ΔH = heat of vaporization, any units desired such as Btu/lb mole (value of ΔH is approximately that at the mean temperature)
R = gas-law constant, units same as $\Delta H/T$, such as Btu/(lb mole)(°R) (see Table E-1)

This may be used for computing vapor pressure at one temperature from a known vapor pressure (such as the boiling point) and the heat of vaporization.

c. Vapor Pressure of Solutions.—Figures of the type of E-16 to E-18 are probably very good ways of presenting vapor-pressure data for solutions, but their use has not been employed to any extent. Data on the vapor pressures for aqua ammonia are given in Tables L-14 and L-15. The same chapter gives additional equilibrium data related to vapor pressures.

4. Latent Heats of Vaporization

a. Heat of Vaporization Chart.—Heats of vaporization for a number of substances are summarized in Fig. E-19 and the accompanying key Table E-12. The chart actually reads the molal entropy of vaporizations, but it is only necessary to multiply by the absolute temperature and divide by the molecular weight to secure the heat of vaporization, that is,

$$L = \frac{T\Delta S}{m} = \frac{\Delta H}{m} \tag{E-12}$$

where L = latent heat vaporization, Btu/lb
T = absolute temperature, °R

ΔS = molal entropy of vaporization, Btu/(°R)(lb mole)
ΔH = molal heat of vaporization, Btu/lb mole
m = molecular weight

b. Estimation of Latent Heats of Vaporization.—The material following gives several methods for estimating latent heats. The choice of method depends on the type of data available and the accuracy required. Figure E-19 may be used for estimating latent heats provided the latent heat is known at two temperatures by constructing the point on the diagram in the same method as given for the vapor-pressure charts. The latent heat of any substance is of course zero at the critical temperature, and this will establish one of the two required values. If the critical pressures and temperatures are known, the latent heat may be estimated conveniently by use of Eq. (E-13) due to Watson.[1]

$$L = L_K \left(\frac{T_c - T}{T_c - T_K}\right)^{0.38} \qquad \text{(E-13)}$$

where L = latent heat desired at temperature T (same units as L_K)
L_K = known latent heat at temperature, T_K
T, T_K = absolute temperatures, °R
T_c = critical temperature, °R

(T, T_K, T_c may also be in °K provided they are all in the same units.)

Watson also gives an equation for estimating the latent heat at the boiling point; however, Eq. (E-14), proposed by Pollara,[2] is more convenient and only slightly less accurate.

$$\Delta H_B = 4.577 \left(\frac{T_c T_B}{T_c - T_B}\right) \log p_c \qquad \text{(E-14)}$$

where ΔH_B = latent heat at atmospheric boiling point, Btu/lb mole
T_c = critical temperature, °R
T_B = atmospheric boiling point, °R
p_c = critical pressure atmospheres

The latent heat of vaporization, at any temperature, may be estimated from the boiling point; the critical pressure and temperature by means of these Eqs. (E-13) and (E-14), or Eq. (E-15) which results from their combination. This equation is believed to be sufficiently accurate for many engineering calculations.

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[1] *Ind. Eng. Chem.*, **35**, 398 (1943).

[2] *J. Phys. Chem.*, **46**, 1163 (1942).

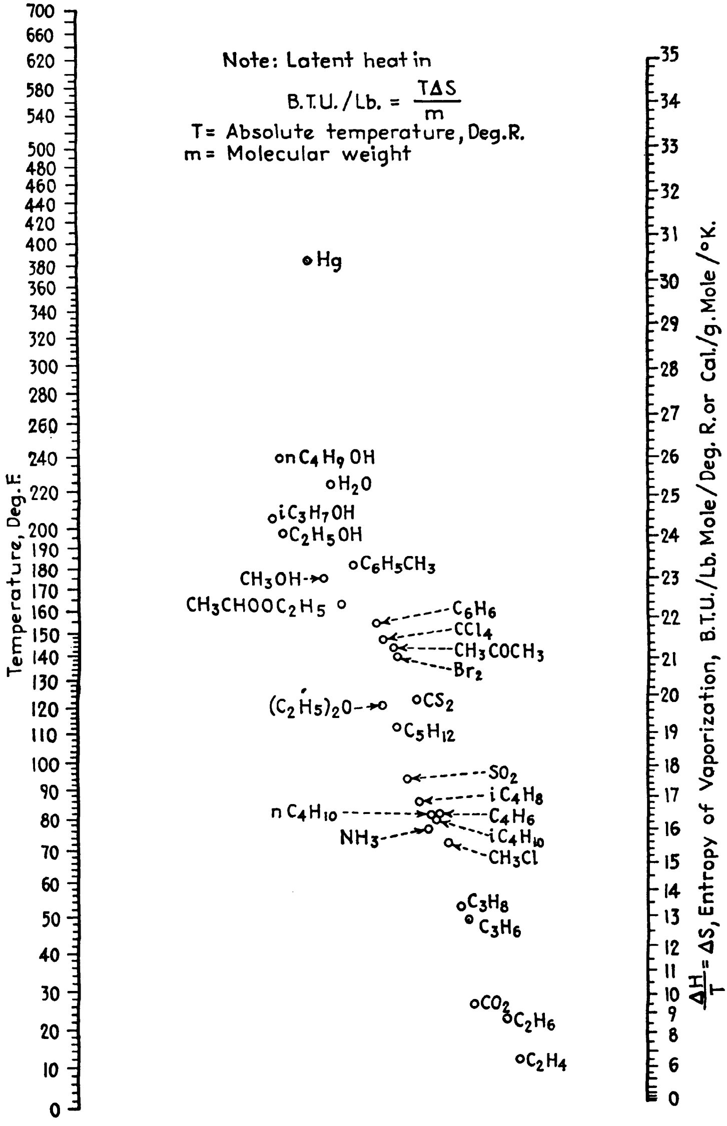

FIG. E-19.—Heats and entropies of vaporization.

TABLE E-12.—KEY FOR FIG. E-19. HEATS OF VAPORIZATION

Substance	Formula	Molecular weight	Principal references
Sulphur dioxide	SO_2	64.06	Perry, "Chemical Engineers' Handbook," 2d ed., 1941.
Isobutylene	$i\text{-}C_4H_8$	56.10	Garner, Adams, and Stuchell, *Petroleum Refiner*, October, 1942.
Normal butane	$n\text{-}C_4H_{10}$	58.10	Dana, Jenkins, Burdick, and Timm, *Refrig. Eng.*, **12**, No. 12, 403 (1926).
1-3, Butadiene	C_4H_6	54.09	Garner, Adams, and Stuchell, *Petroleum Refiner*, October, 1942.
Ammonia	NH_3	17.03	*Bur. Standards Circ.* 142 (1923).
Isobutane	$i\text{-}C_4H_{10}$	58.10	Dana, Jenkins, Burdick, and Timm, *Refrig. Eng.*, **12**, No. 12, 403 (1926).
Methyl chloride	CH_3Cl	50.48	Tanner, Banning, and Mathewson, *Ind. Eng. Chem.*, **31**, 878 (1939).
Propane	C_3H_8	44.09	Dana, Jenkins, Burdick, and Timm, *Refrig. Eng.*, **12**, No. 12, 403 (1926).
Propylene	C_3H_6	42.08	Private source.
Carbon dioxide	CO_2	44.01	*Am. Soc. Refrig. Eng., Circ.* 9 (1926).
Ethane	C_2H_6	30.07	Beall, *Refiner Natural Gasoline Mfr.*, **14**, No. 12, 588 (1935).
Ethylene	C_2H_4	28.05	Private source.
Mercury	Hg	200.61	Kelley, *U.S. Bur. Mines. Bull.* 383 (1935)
Normal butyl alcohol	C_4H_9OH	74.08	Hodgman, "Handbook of Chemistry and Physics," 1940.
Water	H_2O	18.016	Keenan and Keyes, "Thermodynamic Properties of Steam," 1936.
Isopropyl alcohol	$i\text{-}C_3H_7OH$	60.76	Hodgman, "Handbook of Chemistry and Physics," 1940.
Ethyl alcohol	C_2H_5OH	46.05	Fisk, Ginnings, and Holton, *Bur. Standards, J. Research*, **6**, No. 5, 895 (1931).
Toluene	$C_6H_5CH_3$	92.21	Doss, "Physical Properties of the Principal Hydrocarbons," 1940.
Methyl alcohol	CH_3OH	32.03	Hodgman, "Handbook of Chemistry and Physics," 1940.
Ethyl acetate	$CH_3CHOOC_2H_5$	88.06	Hodgman, "Handbook of Chemistry and Physics," 1940.
Benzene	C_6H_6	78.05	Doss, "Physical Properties of the Principal Hydrocarbons," 1940.
Carbon tetrachloride	CCl_4	153.83	Hodgman, "Handbook of Chemistry and Physics," 1940.
Acetone	CH_3COCH_3	58.05	Hodgman, "Handbook of Chemistry and Physics," 1940.
Bromine	Br_2	159.83	Hodgman, "Handbook of Chemistry and Physics," 1940.
Ethyl ether	$(C_2H_5)_2O$	74.08	*Am. Soc. Refrig. Eng., Circ.* 9 (1926).
Carbon disulphide	CS_2	76.12	Hodgman, "Handbook of Chemistry and Physics," 1940.
Normal pentane	C_5H_{12}	72.15	Sage and Lacey, *Ind. Eng. Chem.*, **34**, 730 (1942).

$$\Delta H = 4.577 \left(\frac{T_c T_B}{T_c - T_B}\right)\left(\frac{T_c - T}{T_c - T_B}\right)^{0.38} \log p_c \qquad \text{(E-15)}$$

where ΔH = latent heat (at temperature T), Btu/lb mole
T_c = critical temperature, °R
T_B = boiling point, °R
T = temperature at which latent heat is required, °R
p_c = critical pressure atmospheres

The latent heat may be estimated from vapor-pressure data alone by the Clausius-Clapeyron Eq. (E-11) given under Vapor Pressure. Repeating this in altered form,

$$\Delta H = \frac{2.303\, R T_1 T_2}{T_1 - T_2} \log \frac{p_1}{p_2} \qquad \text{(E-11}a\text{)}$$

where ΔH = molal heat of vaporization, Btu/lb mole
p_1 = vapor pressure at T_1, any units
p_2 = vapor pressure at T_2, units same as p_1
T_1, T_2 = absolute temperature, °R
R = 1.987, the gas-law constant in Btu/(lb mole)(°R)

If only the boiling point of the substance is known, the latent heat may be estimated by the Kistiakowski[1] equation:

$$\Delta H = 8.75 T_B + 4.571 T_B \log T_B \qquad \text{(E-16)}$$

where ΔH = molal heat of vaporization at boiling point, Btu/lb mole
T_B = boiling point, °R

Despite the simplicity of this relation, it is surprisingly accurate for compounds classified by the chemist as nonpolar, but it does give low results for polar compounds such as water, ammonia, most acids, bases, and alcohols.

c. Exact Determination of Latent Heats of Vaporization.—The Clapeyron equation expresses the exact relation between vapor pressures and latent heats.

$$\frac{dp}{dT} = \frac{JL}{T(V_g - V_e)} \qquad \text{(E-17)}$$

where p = vapor pressure, lb/sq ft
T = absolute temperature, °R
J = 778.1, the mechanical equivalent of heat
L = latent heat, Btu/lb
V_g = volume of vapor, cu ft/lb
V_e = volume of liquid, cu ft/lb

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[1] *Z. physik. Chem.*, **107**, 65 (1923).

To compute L, the specific volumes of the gas and liquid must be known and dp/dT obtained by either graphical or analytical differentiation of the vapor-pressure temperature curve. This equation is the basis of the Clausius-Clapeyron and numerous other relations.

The method of Gordon[1] appears quite accurate and permits computation of the latent heats without knowledge of vapor density, though the critical pressure and temperature must be known.

5. Tables and Charts of Thermodynamic Properties of Steam, Propane, Ammonia, and Carbon Dioxide

List of Tables and Charts:

Saturated steam by temperatures	Table E-13
Saturated steam by pressures	Table E-14
Superheated steam	Table E-15
Saturated propane	Table E-16
Superheated propane, temperature entropy diagram	Fig. E-20
Saturated ammonia	Table E-17
Superheated ammonia, Mollier diagram	Fig. E-21
Saturated carbon dioxide	Table E-18

The uses of thermodynamic data presented in this section are manifold. For simple heating and cooling problems the heat supplied or liberated is given by the difference between the final and initial heat content.

$$Q = \Delta H = H_2 - H_1$$

where Q = heat absorbed, Btu/lb
H_2 = heat content, final state, Btu/lb
H_1 = heat content, initial state, Btu/lb

Example E-1 gives the calculation of a refrigeration cycle to illustrate the use of tables and charts. See also the discussion of compression in Chapter K and engines in Chapter I.

Example E-1. Find the power and cooling water requirements for a propane refrigerator supplying 80,000 Btu/hr refrigeration at −20°F (temperature of refrigerant). Cooling water may be assumed to be at 80°F condensing the propane at 100°F.

SOLUTION:

1. Conditions at exit of condenser, 100°F liquid propane is saturated at 188.7 psia

$$h_1 = 264.6 \text{ Btu/lb from Table E-16}$$

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[1] *Ind. Eng. Chem.*, **35**, 851 (1943).

2. After expansion, $-20°F$ propane is saturated at 25.05 psia

$$h_2 = h_1 = 264.6 \text{ Btu/lb (since no heat removed or work performed)}$$

3. After evaporation, $-20°F$ propane saturated vapor at 25.05 psia

$$h_3 = 371.5 \text{ Btu/lb (Table E-16)}$$

4. Refrigeration supplied,

$$h_3 - h_2 = 371.5 - 264.6 = 106.9 \text{ Btu/lb}$$

and

$$\frac{80{,}000}{106.9} = 748 \text{ lb/hr propane circulated}$$

5. Ideal work of compression under adiabatic (no-heat-loss) conditions, $\Delta S = 0$; follow constant entropy line from $-20°F$ saturated propane to 188.7 psi on Fig. E-20

$$h_5 = 413 \text{ Btu/lb}$$
$$\text{work} = h_5 - h_3 = 413 - 371.5 = 41.5 \text{ Btu/lb}$$

6. Actual work of compression, assume compressor efficiency = 75 per cent:

$$\text{Work} = \frac{41.5}{0.75} = 55.3 \text{ Btu/lb}$$

Bhp required to compress 748 lb/hr,

$$\frac{55.3 \times 748}{2544} = 16.25$$
$$(1 \text{ hp} = 2544 \text{ Btu/hr})$$

7. Conditions at exit of compressor,

$$\text{Heat content} = h_6 = h_3 + \text{work of compression,}$$
$$371.5 + 55.3 = 426.8$$

(This corresponds to 151°F if no heat is removed by compressor jackets.)

8. Heat to be removed by cooling and condensing,

$$h_6 - h_1 = 426.8 - 264.6 = 162.2 \text{ Btu/lb}$$

or, for 748 lb/hr of propane,

$$\text{Heat to be removed} = 748 \times 162.2 = 121{,}000 \text{ Btu/hr}$$

9. Cooling water required, assume 10°F rise,

$$\text{Gpm} = \frac{121{,}000}{500 \times 10} = 24$$
$$(1 \text{ gpm} = 500 \text{ lb/hr})$$

TABLE E-13.—PROPERTIES OF SATURATED STEAM: TEMPERATURE TABLE (Abstracted by permission from J. H. Keenan and F. G. Keyes, "Thermodynamic Properties of Steam," published by John Wiley & Sons, Inc.)

Temp., °F	Abs. press., psi	Specific volume		Heat content			Entropy	
		Sat. solid, V_i	Sat. vapor, V_g	Sat. solid, h_i	Subl. L_s	Sat. vapor, h_g	Sat. solid, S_i	Sat. vapor, S_g
−40	0.0019	0.01737	133,900	−177.00	1221.2	1044.2	−0.3654	2.5433
−30	0.0035	0.01738	74,100	−172.63	1221.2	1048.6	−0.3551	2.4860
−20	0.0062	0.01739	42,200	−168.16	1221.2	1053.0	−0.3448	2.4316
−10	0.0108	0.01741	24,670	−163.59	1221.0	1057.4	−0.3346	2.3797
0	0.0185	0.01742	14,770	−158.93	1220.7	1061.8	−0.3241	2.3305
10	0.0309	0.01744	9,050	−154.17	1220.4	1066.2	−0.3141	2.2836
20	0.0505	0.01745	5,658	−149.31	1219.9	1070.6	−0.3038	2.2387
32	0.0885	0.01747	3,306	−143.35	1219.1	1075.8	−0.2916	2.1877

Temp., °F	Abs. press., psi	Specific volume		Heat content			Entropy	
		Sat. liquid, V_l	Sat. vapor, V_g	Sat. liquid, h_l	Evap., L	Sat. vapor, h_g	Sat. liquid, S_l	Sat. vapor, S_g
32	0.08854	0.01602	3306	0.00	1075.8	1075.8	0.000	2.1877
40	0.12170	0.01602	2444	8.05	1071.3	1079.3	0.0162	2.1597
50	0.17811	0.01603	1703.2	18.07	1065.6	1083.7	0.0361	2.1264
60	0.2563	0.01604	1206.7	28.06	1059.9	1088.0	0.0555	2.0948
65	0.3056	0.01605	1021.4	33.05	1057.1	1090.2	0.0651	2.0796
70	0.3631	0.01606	867.9	38.04	1054.3	1092.3	0.0745	2.0647
75	0.4298	0.01607	740.0	43.03	1051.5	1094.5	0.0839	2.0502
80	0.5069	0.01608	633.1	48.02	1048.6	1096.6	0.0932	2.0360
85	0.5959	0.01609	543.5	53.00	1045.8	1098.8	0.1024	2.0222
90	0.6982	0.01610	468.0	57.99	1042.9	1100.9	0.1115	2.0087
95	0.8153	0.01612	404.3	62.98	1040.1	1103.1	0.1205	1.9955
100	0.9492	0.01613	350.4	67.97	1037.2	1105.2	0.1295	1.9826
105	1.1016	0.01615	304.5	72.95	1034.3	1107.3	0.1383	1.9700
110	1.2748	0.01617	265.4	77.94	1031.6	1109.5	0.1471	1.9577
115	1.4709	0.01618	231.9	82.93	1028.7	1111.6	0.1559	1.9457
120	1.6924	0.01620	203.27	87.92	1025.8	1113.7	0.1645	1.9339
130	2.2225	0.01625	157.34	97.90	1020.0	1117.9	0.1816	1.9112
140	2.8886	0.01629	123.01	107.89	1014.1	1122.0	0.1984	1.8894
150	3.718	0.01634	97.07	117.89	1008.2	1126.1	0.2149	1.8685
160	4.741	0.01639	77.29	127.89	1002.3	1130.2	0.2311	1.8485
170	5.992	0.01645	62.06	137.90	996.3	1134.2	0.2472	1.8293
180	7.510	0.01651	50.23	147.92	990.2	1138.1	0.2630	1.8109
190	9.339	0.01657	40.96	157.95	984.1	1142.0	0.2785	1.7932
200	11.526	0.01663	33.64	167.99	977.9	1145.9	0.2938	1.7762
210	14.123	0.01670	27.82	178.05	971.6	1149.7	0.3090	1.7598
220	17.186	0.01677	23.15	188.13	965.2	1153.4	0.3239	1.7440
230	20.780	0.01684	19.382	198.23	958.8	1157.0	0.3387	1.7288
240	24.969	0.01692	16.323	208.34	952.2	1160.5	0.3531	1.7140
250	29.825	0.01700	13.821	218.48	945.5	1164.0	0.3675	1.6998
260	35.429	0.01709	11.763	228.64	938.7	1167.3	0.3817	1.6860
270	41.858	0.01717	10.061	238.84	931.8	1170.6	0.3958	1.6727
280	49.203	0.01726	8.645	249.06	924.7	1173.8	0.4096	1.6597
290	57.556	0.01735	7.461	259.31	917.5	1176.8	0.4234	1.6472
300	67.013	0.01745	6.466	269.59	910.1	1179.7	0.4369	1.6350
310	77.68	0.01755	5.626	279.92	902.6	1182.5	0.4504	1.6231
320	89.66	0.01765	4.914	290.28	894.9	1185.2	0.4637	1.6115
330	103.06	0.01776	4.307	300.68	887.0	1187.7	0.4769	1.6002
340	118.01	0.01787	3.788	311.13	879.0	1190.1	0.4900	1.5891
350	134.63	0.01799	3.342	321.63	870.7	1192.3	0.5029	1.5783
360	153.04	0.01811	2.957	332.18	862.2	1194.4	0.5158	1.5677
370	173.37	0.01823	2.625	342.79	853.5	1196.3	0.5286	1.5573
380	195.77	0.01836	2.335	353.45	844.6	1198.1	0.5413	1.5471
390	220.37	0.01850	2.0836	364.17	835.4	1199.6	0.5539	1.5371
400	247.31	0.01864	1.8633	374.97	826.0	1201.0	0.5664	1.5272
450	422.6	0.0194	1.0993	430.1	774.5	1204.6	0.6280	1.4793
500	680.8	0.0204	0.6749	487.8	713.9	1201.7	0.6887	1.4325
550	1045.2	0.0218	0.4240	549.3	640.8	1190.0	0.7497	1.3843
600	1542.9	0.0236	0.2668	617.0	548.5	1165.5	0.8131	1.3307
650	2208.2	0.0268	0.1616	695.7	422.8	1118.5	0.8828	1.2637
700	3093.7	0.0369	0.0761	823.3	172.1	995.4	0.9905	1.1389
705.4	3206.2	0.0503	0.0503	902.7	0	902.7	1.0580	1.0580

TABLE E-14.—PROPERTIES OF SATURATED STEAM: PRESSURE TABLE
(Abstracted by permission from J. H. Keenan and F. G. Keyes, "Thermodynamic Properties of Steam," published by John Wiley & Sons, Inc.)

Abs. press., psi	Temp., °F	Specific volume		Heat content			Entropy	
		Sat. liquid, V_l	Sat. vapor, V_g	Sat. liquid, h_l	Evap., L	Sat. vapor, h_g	Sat. liquid, S_l	Sat. vapor, S_g
1.0	101.74	0.01614	333.6	69.70	1036.3	1106.0	0.1326	1.9782
5.0	162.24	0.01640	73.52	130.13	1001.0	1131.1	0.2347	1.8441
10	193.21	0.01659	38.42	161.17	982.1	1143.3	0.2835	1.7876
14.7	212.00	0.01672	26.80	180.07	970.3	1150.4	0.3120	1.7566
20	227.96	0.01683	20.089	196.16	960.1	1156.3	0.3356	1.7319
25	240.07	0.01692	16.303	208.42	952.1	1160.6	0.3533	1.7139
30	250.33	0.01701	13.746	218.82	945.3	1164.1	0.3680	1.6993
35	259.28	0.01708	11.898	227.91	939.2	1167.1	0.3807	1.6870
40	267.25	0.01715	10.498	236.03	933.7	1169.7	0.3919	1.6763
45	274.44	0.01721	9.401	243.36	928.6	1172.0	0.4019	1.6669
50	281.01	0.01727	8.515	250.09	924.0	1174.1	0.4110	1.6585
55	287.07	0.01732	7.787	256.30	919.6	1175.9	0.4193	1.6509
60	292.71	0.01738	7.175	262.09	915.5	1177.6	0.4270	1.6438
70	302.92	0.01748	6.206	272.61	907.9	1180.6	0.4409	1.6315
80	312.03	0.01757	5.472	282.02	901.1	1183.1	0.4531	1.6207
90	320.27	0.01766	4.896	290.56	894.7	1185.3	0.4641	1.6112
100	327.81	0.01774	4.432	298.40	888.8	1187.2	0.4740	1.6026
110	334.77	0.01782	4.049	305.66	883.2	1188.9	0.4832	1.5948
120	341.25	0.01789	3.728	312.44	877.9	1190.4	0.4916	1.5878
130	347.32	0.01796	3.455	318.81	872.9	1191.7	0.4995	1.5812
140	353.02	0.01802	3.220	324.82	868.2	1193.0	0.5069	1.5751
160	363.53	0.01815	2.834	335.93	859.2	1195.1	0.5204	1.5640
180	373.06	0.01827	2.532	346.03	850.8	1196.9	0.5325	1.5542
200	381.79	0.01839	2.288	355.36	843.0	1198.4	0.5435	1.5453
250	400.95	0.01865	1.8438	376.00	825.1	1201.1	0.5675	1.5263
300	417.33	0.01890	1.5433	393.84	809.0	1202.8	0.5879	1.5104
350	431.72	0.01913	1.3260	409.69	794.2	1203.9	0.6056	1.4966
400	444.59	0.0193	1.1613	424.0	780.5	1204.5	0.6214	1.4844
500	467.01	0.0197	0.9278	449.4	755.0	1204.4	0.6487	1.4634
600	486.21	0.0201	0.7698	471.6	731.6	1203.2	0.6720	1.4454
800	518.23	0.0209	0.5687	509.7	688.9	1198.6	0.7108	1.4153
1,000	544.61	0.0216	0.4456	542.4	649.4	1191.8	0.7430	1.3897
1,500	596.23	0.0235	0.2765	611.6	556.3	1167.9	0.8082	1.3351
2,000	635.82	0.0257	0.1878	671.7	463.4	1135.1	0.8619	1.2849
2,500	668.13	0.0287	0.1307	730.6	360.5	1091.1	0.9126	1.2322
3,000	695.36	0.0346	0.0858	802.5	217.8	1020.3	0.9731	1.1615
3,206.2	705.40	0.0503	0.0503	902.7	0	902.7	1.0580	1.0580

TABLE E-15.—PROPERTIES OF SUPERHEATED STEAM

(Abstracted by permission from J. H. Keenan and F. G. Keyes, "Thermodynamic Properties of Steam," published by John Wiley & Sons, Inc.)

Abs. press., psi (sat. temp.)		Temperature, degrees Fahrenheit																			
		220°	240°	260°	280°	300°	320°	340°	360°	380°	400°	420°	440°	460°	500°	600°	800°	1000°	1200°	1400°	1600°
1 (101.74)	v	404.5	416.5	428.4	440.4	452.3	464.2	476.2	488.1	500.0	512.0	523.9	535.8	547.7	571.6	631.2	750.4	869.5	988.7	1107.8	1227.0
	h	1159.5	1168.5	1177.6	1186.7	1195.8	1204.9	1214.1	1223.3	1232.5	1241.7	1251.0	1260.3	1269.6	1288.3	1335.7	1432.8	1533.5	1637.7	1745.7	1857.5
	s	2.0647	2.0779	2.0907	2.1031	2.1153	2.1271	2.1387	2.1501	2.1612	2.1720	2.1827	2.1931	2.2034	2.2233	2.2702	2.3542	2.4283	2.4952	2.5566	2.6137
5 (162.24)	v	80.59	83.01	85.43	87.85	90.25	92.66	95.06	97.46	99.86	102.26	104.65	107.04	109.44	114.22	126.16	150.03	173.87	197.71	221.6	245.4
	h	1158.1	1167.3	1176.5	1185.7	1195.0	1204.2	1213.4	1222.7	1231.9	1241.2	1250.5	1259.8	1269.2	1288.0	1335.4	1432.7	1533.4	1637.7	1745.7	1857.4
	s	1.8857	1.8991	1.9121	1.9247	1.9370	1.9490	1.9607	1.9721	1.9833	1.9942	2.0049	2.0154	2.0256	2.0456	2.0927	2.1767	2.2509	2.3178	2.3792	2.4363
10 (193.21)	v	40.09	41.33	42.56	43.78	45.00	46.21	47.42	48.63	49.84	51.04	52.24	53.45	54.65	57.05	63.03	74.98	86.92	98.84	110.77	122.69
	h	1156.2	1165.7	1175.1	1184.5	1193.9	1203.2	1212.5	1221.9	1231.2	1240.6	1249.9	1259.3	1268.7	1287.5	1335.1	1432.5	1533.2	1637.6	1745.6	1857.3
	s	1.8071	1.8208	1.8341	1.8470	1.8595	1.8716	1.8834	1.8950	1.9062	1.9172	1.9280	1.9385	1.9488	1.9689	2.0160	2.1002	2.1744	2.2413	2.3028	2.3598
14.696 (212.00)	v	27.15	28.00	28.85	29.70	30.53	31.37	32.20	33.03	33.85	34.68	35.50	36.32	37.14	38.78	42.86	51.00	59.13	67.25	75.37	83.48
	h	1154.4	1164.2	1173.8	1183.3	1192.8	1202.3	1211.7	1221.1	1230.5	1239.9	1249.3	1258.8	1268.2	1287.1	1334.8	1432.3	1533.1	1637.5	1745.5	1857.3
	s	1.7624	1.7766	1.7902	1.8033	1.8160	1.8283	1.8402	1.8518	1.8631	1.8743	1.8850	1.8956	1.9060	1.9261	1.9734	2.0576	2.1319	2.1989	2.2603	2.3174
20 (227.96)	v	......	20.48	21.11	21.74	22.36	22.98	23.60	24.21	24.82	25.43	26.04	26.65	27.25	28.46	31.47	37.46	43.44	49.41	55.37	61.34
	h	......	1162.3	1172.2	1182.0	1191.6	1201.2	1210.8	1220.3	1229.7	1239.2	1248.7	1258.2	1267.6	1286.6	1334.4	1432.1	1533.0	1637.4	1745.4	1857.2
	s	......	1.7405	1.7545	1.7679	1.7808	1.7932	1.8053	1.8170	1.8285	1.8396	1.8505	1.8612	1.8716	1.8918	1.9392	2.0235	2.0978	2.1648	2.2263	2.2834
25 (240.07)	v	......	......	16.819	17.330	17.836	18.337	18.834	19.329	19.821	20.31	20.80	21.29	21.77	22.74	25.16	29.96	34.74	35.92	44.30	49.07
	h	......	......	1170.7	1180.6	1190.5	1200.2	1209.8	1219.4	1229.0	1238.5	1248.1	1257.6	1267.1	1286.2	1334.1	1431.9	1532.8	1637.3	1745.3	1857.2
	s	......	......	1.7282	1.7418	1.7550	1.7676	1.7798	1.7917	1.8032	1.8144	1.8254	1.8361	1.8465	1.8668	1.9144	1.9988	2.0732	2.1402	2.2017	2.2587
30 (250.33)	v	......	......	13.957	14.390	14.816	15.238	15.657	16.072	16.485	16.897	17.306	17.714	18.121	18.933	20.95	24.96	28.95	32.93	36.91	40.89
	h	......	......	1169.1	1179.3	1189.3	1199.1	1208.9	1218.6	1228.3	1237.9	1247.5	1257.0	1266.6	1285.7	1333.8	1431.7	1532.7	1637.2	1745.3	1857.1
	s	......	......	1.7063	1.7203	1.7336	1.7464	1.7588	1.7708	1.7824	1.7937	1.8047	1.8155	1.8260	1.8464	1.8940	1.9786	2.0530	2.1201	2.1815	2.2386
35 (259.28)	v	......	......	11.911	12.288	12.659	13.025	13.387	13.746	14.103	14.457	14.810	15.162	15.512	16.210	17.943	21.38	24.81	28.22	31.63	35.04
	h	......	......	1167.5	1177.9	1188.1	1198.1	1208.0	1217.8	1227.5	1237.2	1246.8	1256.4	1266.1	1285.3	1333.5	1431.5	1532.6	1637.1	1745.2	1857.0
	s	......	......	1.6875	1.7018	1.7154	1.7284	1.7409	1.7530	1.7647	1.7761	1.7872	1.7980	1.8086	1.8290	1.8768	1.9615	2.0360	2.1030	2.1645	2.2216
40 (267.25)	v	......	......	......	10.711	11.040	11.364	11.684	12.001	12.315	12.628	12.938	13.247	13.555	14.168	15.688	18.702	21.70	24.69	27.68	30.66
	h	......	......	......	1176.5	1186.8	1197.0	1207.0	1216.9	1226.7	1236.5	1246.2	1255.9	1265.5	1284.8	1333.1	1431.3	1532.4	1637.0	1745.1	1857.0
	s	......	......	......	1.6855	1.6994	1.7126	1.7252	1.7375	1.7493	1.7608	1.7719	1.7828	1.7934	1.8140	1.8619	1.9467	2.0212	2.0883	2.1498	2.2069
50 (281.01)	v	......	......	......	......	8.773	9.038	9.299	9.557	9.812	10.065	10.317	10.567	10.815	11.309	12.532	14.950	17.352	19.747	22.14	24.53
	h	......	......	......	......	1184.3	1194.8	1205.0	1215.2	1225.2	1235.1	1244.9	1254.7	1264.5	1283.9	1332.5	1430.9	1532.1	1636.8	1745.0	1856.8
	s	......	......	......	......	1.6721	1.6857	1.6987	1.7112	1.7233	1.7349	1.7462	1.7572	1.7680	1.7887	1.8368	1.9219	1.9964	2.0636	2.1251	2.1822

TABLE E-15.—PROPERTIES OF SUPERHEATED STEAM (*Continued*)

Abs. press., psi (sat. temp.)		Temperature, degrees Fahrenheit																			
		220°	240°	260°	280°	300°	320°	340°	360°	380°	400°	420°	440°	460°	500°	600°	800°	1000°	1200°	1400°	1600°
55 (287.07)	*v*	......	......	......	......	7.947	8.192	8.432	8.668	8.902	9.134	9.364	9.592	9.819	10.269	11.384	13.586	15.771	17.950	20.12	22.30
	h	......	......	......	......	1183.0	1193.6	1204 0	1214.3	1224.4	1234.3	1244.3	1254.1	1263 9	1283.4	1332.1	1430.7	1532.0	1636.7	1744.9	1856.8
	s	......	......	......	......	1.6602	1.6740	1.6872	1.6999	1.7120	1.7238	1.7351	1.7462	1.7570	1.7778	1.8261	1.9112	1.9859	2.0530	2.1146	2.1717
60 (292.71)	*v*	......	......	......	......	7.259	7.486	7.708	7.927	8.143	8.357	8.569	8.779	8.988	9.403	10.427	12.449	14.454	16.451	18.446	20.44
	h	......	......	......	......	1181.6	1192.5	1203.0	1213.4	1223.6	1233.6	1243.6	1253.5	1263.4	1283.0	1331.8	1430.5	1531.9	1636.6	1744.8	1856.7
	s	......	......	......	......	1.6492	1.6633	1.6766	1.6894	1.7017	1.7135	1.7250	1.7361	1.7470	1.7678	1.8162	1.9015	1.9762	2.0434	2.1049	2.1621
70 (302.92)	*v*	......	......	......	......	......	6.376	6.571	6.762	6.950	7.136	7.320	7.502	7.683	8.041	8.924	10.662	12.383	14.097	15.808	17.516
	h	......	......	......	......	......	1190.1	1201.0	1211.5	1221.9	1232.1	1242.3	1252.3	1262.2	1282.0	1331.1	1430.1	1531.6	1636.3	1744.6	1856.6
	s	......	......	......	......	......	1.6438	1.6576	1.6707	1.6832	1.6952	1.7068	1.7181	1.7291	1.7501	1.7988	1.8843	1.9591	2.0263	2.0879	2.1451
80 (312.03)	*v*	......	......	......	......	......	5.543	5.718	5.888	6.055	6.220	6.383	6.544	6.704	7.020	7.797	9.322	10.830	12.332	13.830	15.325
	h	......	......	......	......	......	1187.6	1198.8	1209.7	1220.3	1230.7	1240.9	1251.1	1261 1	1281.1	1330.5	1429.7	1531.3	1636.2	1744.5	1856.5
	s	......	......	......	......	......	1.6266	1.6407	1.6541	1.6669	1.6791	1.6909	1.7023	1.7134	1.7346	1.7836	1.8694	1.9442	2.0115	2.0731	2.1303
90 (320.27)	*v*	......	......	......	......	......	......	5.053	5.208	5.359	5.508	5.654	5.799	5.942	6.225	6.920	8.279	9.623	10.959	12.291	13.621
	h	......	......	......	......	......	......	1196.6	1207.7	1218.6	1229.1	1239.5	1249.8	1260.0	1280.1	1329.8	1429.3	1531.0	1635.9	1744.3	1856.4
	s	......	......	......	......	......	......	1.6256	1.6393	1.6523	1.6648	1.6767	1.6883	1.6995	1.7209	1.7702	1.8562	1.9311	1.9984	2.0601	2.1173
100 (327.81)	*v*	......	......	......	......	......	......	4.521	4.663	4.801	4.937	5.071	5.202	5.333	5.589	6.218	7.446	8.656	9.860	11.060	12.258
	h	......	......	......	......	......	......	1194.3	1205.7	1216.8	1227.6	1238.1	1248.6	1258.8	1279.1	1329.1	1428.9	1530.8	1635.7	1744.2	1856.2
	s	......	......	......	......	......	......	1.6117	1.6258	1.6391	1.6518	1.6639	1.6756	1.6869	1.7085	1.7581	1.8443	1.9193	1.9867	2.0484	2.1056
110 (334.77)	*v*	......	......	......	......	......	......	4.085	4.216	4.345	4.470	4.593	4.714	4.834	5.069	5.644	6.763	7.866	8.961	10.053	11.142
	h	......	......	......	......	......	......	1192.0	1203.7	1215.0	1226.0	1236.7	1247.3	1257.7	1278.2	1328.4	1428.5	1530.5	1635.5	1744.0	1856.1
	s	......	......	......	......	......	......	1.5988	1.6133	1.6269	1.6398	1.6521	1.6640	1.6754	1.6972	1.7471	1.8336	1.9087	1.9761	2.0378	2.0951
120 (341.25)	*v*	......	......	......	......	......	......	......	3.844	3.964	4.081	4.195	4.307	4.418	4.636	5.165	6.195	7.207	8.212	9.214	10.213
	h	......	......	......	......	......	......	......	1201.6	1213.2	1224.4	1235.3	1246.0	1256.5	1277.2	1327.7	1428.1	1530.2	1635.3	1743.9	1856.0
	s	......	......	......	......	......	......	......	1.6017	1.6156	1.6287	1.6413	1.6533	1.6649	1.6869	1.7370	1.8237	1.8990	1.9664	2.0281	2.0854
130 (347.32)	*v*	......	......	......	......	......	......	......	3.529	3.641	3.751	3.858	3.963	4.066	4.269	4.761	5.714	6.650	7 579	8.503	9.426
	h	......	......	......	......	......	......	......	1199.5	1211.3	1222.7	1233 8	1244.6	1255.3	1276.2	1327.0	1427.7	1529.9	1635.1	1743.7	1855.9
	s	......	......	......	......	......	......	......	1.5908	1.6050	1.6184	1.6312	1.6433	1.6550	1.6773	1.7277	1.8147	1.8900	1.9575	2.0193	2.0765
140 (353.02)	*v*	......	......	......	......	......	......	......	3.258	3.365	3.468	3.569	3.667	3.764	3.954	4 413	5.301	6.172	7.035	7.895	8.752
	h	......	......	......	......	......	......	......	1197.3	1209.4	1221.1	1232.3	1243.3	1254 1	1275.2	1326.4	1427.3	1529.7	1634.9	1743.5	1855.7
	s	......	......	......	......	......	......	......	1.5804	1.5950	1.6087	1.6217	1.6340	1.6458	1.6683	1.7190	1.8063	1.8817	1.9493	2.0110	2.0683
160 (363.53)	*v*	......	......	......	......	......	......	......	......	2.914	3.008	3.098	3.187	3.273	3.443	3.849	4.631	5.396	6 152	6.906	7.656
	h	......	......	......	......	......	......	......	......	1205.5	1217.6	1229.3	1240.6	1251.6	1273.1	1325.0	1426.4	1529.1	1634.5	1743.2	1855.5
	s	......	......	......	......	......	......	......	......	1.5766	1.5908	1.6042	1.6169	1.6291	1.6519	1.7033	1.7911	1.8667	1.9344	1.9962	2.0535
180 (373.06)	*v*	......	......	......	......	......	......	......	......	2.563	2.649	2.732	2.813	2.891	3.044	3.411	4.110	4.792	5.466	6.136	6.804
	h	......	......	......	......	......	......	......	......	1201.4	1214.0	1226.1	1237.8	1249.1	1271.0	1323.5	1425.6	1528.6	1634.1	1742.9	1855.2
	s	......	......	......	......	......	......	......	......	1.5596	1.5745	1.5884	1.6015	1.6139	1.6373	1.6894	1.7776	1.8534	1.9212	1.9831	2.0404

200 (381.79)	*v*	......	......	......	......	......	......	......	......	......	2.361	2.438	2.513	2.585	2.726	3.060	3.693	4.309	4.917	5.521	6.123
	h	......	......	......	......	......	......	......	......	......	1210.3	1222.9	1234.9	1246.5	1268.9	1322.1	1424.8	1528.0	1633.7	1742.6	1855.0
	s	......	......	......	......	......	......	......	......	......	1.5594	1.5738	1.5873	1.6001	1.6240	1.6767	1.7655	1.8415	1.9094	1.9713	2.0287
250 (400.95)	*v*	......	......	......	......	......	......	......	......	......	......	1.9077	1.9717	2.033	2.151	2.427	2.942	3.439	3.928	4.413	4.896
	h	......	......	......	......	......	......	......	......	......	......	1214.2	1227.3	1239.7	1263.4	1318.5	1422.7	1526.6	1632.7	1741.8	1854.4
	s	......	......	......	......	......	......	......	......	......	......	1.5414	1.5560	1.5697	1.5949	1.6495	1.7397	1.8162	1.8843	1.9464	2.0039
300 (417.33)	*v*	......	......	......	......	......	......	......	......	......	......	1.5513	1.6090	1.6638	1.7675	2.005	2.442	2.859	3.269	3.674	4.078
	h	......	......	......	......	......	......	......	......	......	......	1204.8	1219.1	1232.5	1257.6	1314.7	1420.6	1525.2	1631.7	1741.0	1853.7
	s	......	......	......	......	......	......	......	......	......	......	1.5126	1.5286	1.5434	1.5701	1.6268	1.7184	1.7954	1.8638	1.9260	1.9835
350 (431.72)	*v*	......	......	......	......	......	......	......	......	......	......	......	1.3478	1.3984	1.4923	1.7036	2.084	2.445	2.798	3.147	3.493
	h	......	......	......	......	......	......	......	......	......	......	......	1210.3	1224.8	1251.5	1310.9	1418.5	1523.8	1630.7	1740.3	1853.1
	s	......	......	......	......	......	......	......	......	......	......	......	1.5037	1.5197	1.5481	1.6070	1.7002	1.7777	1.8463	1.9086	1.9663
400 (444.59)	*v*	......	......	......	......	......	......	......	......	......	......	......	......	1.1978	1.2851	1.4770	1.8161	2.134	2.445	2.751	3.055
	h	......	......	......	......	......	......	......	......	......	......	......	......	1216.5	1245.1	1306.9	1416.4	1522.4	1629.6	1739.5	1852.5
	s	......	......	......	......	......	......	......	......	......	......	......	......	1.4977	1.5281	1.5894	1.6842	1.7623	1.8311	1.8936	1.9513
500 (467.01)	*v*	......	......	......	......	......	......	......	......	......	......	......	......	......	0.9927	1.1591	1.4405	1.6996	1.9504	2.197	2.442
	h	......	......	......	......	......	......	......	......	......	......	......	......	......	1231.3	1298.6	1412.1	1519.6	1627.6	1737.9	1851.3
	s	......	......	......	......	......	......	......	......	......	......	......	......	......	1.4919	1.5588	1.6571	1.7363	1.8056	1.8683	1.9262
600 (486.21)	*v*	......	......	......	......	......	......	......	......	......	......	......	......	......	0.7947	0.9463	1.1899	1.4096	1.6208	1.8279	2.033
	h	......	......	......	......	......	......	......	......	......	......	......	......	......	1215.7	1289.9	1407.7	1516.7	1625.5	1736.3	1850.0
	s	......	......	......	......	......	......	......	......	......	......	......	......	......	1.4586	1.5323	1.6343	1.7147	1.7846	1.8476	1.9056
800 (518.23)	*v*	......	......	......	......	......	......	......	......	......	......	......	......	......	......	0.6779	0.8763	1.0470	1.2088	1.3662	1.5214
	h	......	......	......	......	......	......	......	......	......	......	......	......	......	......	1270.7	1398.6	1511.0	1621.4	1733.2	1847.5
	s	......	......	......	......	......	......	......	......	......	......	......	......	......	......	1.4863	1.5972	1.6801	1.7510	1.8146	1.8729
1000 (544.61)	*v*	......	......	......	......	......	......	......	......	......	......	......	......	......	......	0.5140	0.6878	0.8294	0.9615	1.0893	1.2146
	h	......	......	......	......	......	......	......	......	......	......	......	......	......	......	1248.8	1389.2	1505.1	1617.3	1730.0	1845.0
	s	......	......	......	......	......	......	......	......	......	......	......	......	......	......	1.4450	1.5670	1.6525	1.7245	1.7886	1.8474
2000 (635.82)	*v*	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	0.3074	0.3935	0.4668	0.5352	0.6011
	h	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	1335.5	1474.5	1596.1	1714.1	1832.5
	s	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	1.4576	1.5603	1.6384	1.7055	1.7660
3206.2 (705.40)	*v*	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	0.1583	0.2288	0.2806	0.3267	0.3703
	h	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	1250.5	1434.7	1569.8	1694.6	1817.2
	s	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	1.3508	1.4874	1.5742	1.6452	1.7080
4000	*v*	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	0.1052	0.1743	0.2192	0.2581	0.2943
	h	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	1174.8	1406.8	1552.1	1681.7	1807.2
	s	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	1.2757	1.4482	1.5417	1.6154	1.6795

TABLE E-16.—THERMODYNAMIC PROPERTIES OF SATURATED PROPANE
[Stearns and George, *Ind. Eng. Chem.*, **35**, 602 (1943). By permission of the American Chemical Society]

Temp. t, °F	Pressure		Volume, cu ft/lb		Heat content, Btu/lb		Latent heat L, Btu/lb	Entropy, Btu/(lb)(°F)	
	Psia p	Psig gp	Liquid v	Vapor V	Liquid h	Vapor H		Liquid s	Vapor S
−80	5.65	......	0.0265	16.2	162.6	354.0	191.4	0.8794	1.3832
−78	6.00	.....	0.0266	15.3	163.6	354.6	191.0	0.8821	1.3822
−76	6.32	......	0.0266	14.6	164.6	355.2	190.6	0.8847	1.3812
−74	6.71	......	0.0267	13.8	165.6	355.8	190.2	0.8874	1.3801
−72	7.18	......	0.0268	13.0	166.6	356.4	189.8	0.8900	1.3791
−70	7.48	......	0.0268	12.5	167.6	357.0	189.4	0.8927	1.3781
−68	7.91	......	0.0268	11.9	168.6	357.6	189.0	0.8954	1.3773
−66	8.33	......	0.0269	11.3	169.7	358.2	188.5	0.8980	1.3765
−64	8.80	......	0.0269	10.8	170.7	358.8	188.1	0.9007	1.3756
−62	9.28	......	0.0270	10.3	171.7	359.4	187.7	0.9033	1.3748
−60	9.78	......	0.02703	9.77	172.7	360.0	187.3	0.9060	1.3740
−58	10.29	......	0.02709	9.33	173.7	360.6	186.9	0.9086	1.3732
−56	10.80	......	0.02715	8.92	174.7	361.1	186.4	0.9111	1.3725
−54	11.36	......	0.02721	8.51	175.8	361.7	185.9	0.9137	1.3717
−52	11.95	......	0.02727	8.12	176.8	362.3	185.5	0.9162	1.3710
−50	12.60	......	0.02733	7.73	177.8	362.8	185.0	0.9188	1.3702
−48	13.20	......	0.02739	7.50	178.8	363.4	184.6	0.9213	1.3696
−46	13.85	......	0.02745	7.06	179.9	364.0	184.1	0.9238	1.3689
−44	14.52	......	0.02751	6.74	180.9	364.6	183.8	0.9264	1.3683
−42	15.28	......	0.02757	6.42	181.9	365.2	183.3	0.9289	1.3676
−40	16.00	1.30	0.02763	6.16	183.0	365.7	182.7	0.9315	1.3670
−38	16.79	2.09	0.02769	5.92	184.0	366.3	182.3	0.9340	1.3664
−36	17.56	2.86	0.02775	5.66	185.1	366.9	181.8	0.9365	1.3658
−34	18.40	3.70	0.02782	5.44	186.2	367.5	181.3	0.9391	1.3652
−32	19.30	4.60	0.02788	5.22	187.3	368.0	180.7	0.9416	1.3646
−30	20.18	5.48	0.02794	5.02	188.4	368.6	180.2	0.9441	1.3640
−28	21.05	6.35	0.02800	4.82	189.4	369.2	179.7	0.9467	1.3634
−26	22.01	7.31	0.02807	4.63	190.5	369.8	179.3	0.9492	1.3628
−24	22.98	8.28	0.02813	4.44	191.6	370.3	178.7	0.9517	1.3622
−22	23.98	9.28	0.02820	4.25	192.7	370.9	178.2	0.9543	1.3616
−20	25.05	10.35	0.02826	4.06	193.8	371.5	177.7	0.9568	1.3610
−18	26.15	11.45	0.02833	3.90	194.9	372.1	177.2	0.9592	1.3604
−16	27.30	12.60	0.02839	3.76	196.0	372.7	176.6	0.9617	1.3599
−14	28.50	13.80	0.02846	3.61	197.1	373.2	176.1	0.9641	1.3593
−12	29.70	15.00	0.02852	3.47	198.2	373.8	175.6	0.9666	1.3588

TABLE E-16.—THERMODYNAMIC PROPERTIES OF SATURATED PROPANE (*Continued*)

Temp. t, °F	Pressure		Volume, cu ft/lb		Heat content, Btu/lb		Latent heat L, Btu/lb	Entropy, Btu/(lb)(°F)	
	Psia p	Psig gp	Liquid v	Vapor V	Liquid h	Vapor H		Liquid s	Vapor S
−10	30.95	16.25	0.02859	3.33	199.4	374.4	175.0	0.9690	1.3582
− 8	32.23	17.53	0.02866	3.20	200.5	375.0	174.5	0.9714	1.3577
− 6	33.55	18.85	0.02873	3.08	201.6	375.5	173.9	0.9739	1.3571
− 4	35.00	20.30	0.02879	2.98	202.7	376.1	173.4	0.9763	1.3566
− 2	36.40	21.70	0.02886	2.86	203.8	376.7	172.8	0.9788	1.3560
0	37.81	23.11	0.02893	2.74	205.0	377.2	172.2	0.9812	1.3555
+ 2	39.30	24.60	0.02900	2.66	206.1	377.8	171.6	0.9836	1.3550
4	40.85	26.15	0.02908	2.56	207.2	378.3	171.1	0.9860	1.3545
6	42.50	27.80	0.02915	2.47	208.4	378.9	170.5	0.9884	1.3541
8	44.13	29.43	0.02923	2.38	209.6	379.5	169.9	0.9908	1.3536
10	45.85	31.15	0.02930	2.30	210.7	380.0	169.3	0.9932	1.3531
12	47.55	32.85	0.02938	2.22	211.9	380.6	168.7	0.9956	1.3527
14	49.35	34.65	0.02946	2.14	213.1	381.1	168.0	0.9979	1.3523
16	51.20	36.50	0.02954	2.08	214.2	381.6	167.4	1.0003	1.3518
18	53.10	38.40	0.02962	2.00	215.4	382.1	166.7	1.0026	1.3514
20	55.00	40.30	0.02970	1.93	216.6	382.6	166.0	1.0050	1.3510
22	57.05	42.35	0.02978	1.86	217.7	383.1	165.4	1.0073	1.3506
24	59.10	44.40	0.02986	1.79	218.8	383.6	164.8	1.0097	1.3502
26	61.25	46.55	0.02995	1.73	220.0	384.1	164.2	1.0120	1.3499
28	63.45	48.75	0.03003	1.67	221.2	384.6	163.5	1.0144	1.3495
30	65.70	51.00	0.03011	1.60	222.3	385.1	162.8	1.0167	1.3491
32	67.95	53.25	0.03020	1.54	223.4	385.6	162.2	1.0190	1.3487
34	70.33	55.63	0.03029	1.48	224.5	386.1	161.5	1.0213	1.3484
36	72.75	58.05	0.03037	1.43	225.6	386.6	160.8	1.0237	1.3480
38	75.20	60.50	0.03046	1.39	226.8	387.1	160.2	1.0260	1.3477
40	77.80	63.10	0.03055	1.33	227.9	387.5	159.6	1.0283	1.3473
42	80.40	65.70	0.03064	1.28	229.1	388.0	158.9	1.0306	1.3470
44	83.05	68.35	0.03073	1.25	230.2	388.5	158.2	1.0329	1.3466
46	85.83	71.13	0.03083	1.21	231.4	389.0	157.5	1.0352	1.3463
48	88.65	73.95	0.03092	1.17	232.6	389.5	156.8	1.0375	1.3459
50	91.50	76.80	0.03101	1.14	233.8	389.9	156.1	1.0398	1.3456
52	94.50	79.80	0.03111	1.10	234.9	390.4	155.4	1.0421	1.3453
54	97.5	82.80	0.03121	1.07	236.1	390.8	154.7	1.0443	1.3450
56	100.6	85.9	0.03130	1.04	237.3	391.3	154.0	1.0466	1.3447
58	103.7	89.0	0.03140	1.01	238.5	391.7	153.3	1.0488	1.3444

TABLE E-16.—THERMODYNAMIC PROPERTIES OF SATURATED PROPANE (*Continued*)

Temp. t, °F	Pressure		Volume, cu ft/lb		Heat content, Btu/lb		Latent heat L, Btu/lb	Entropy, Btu/(lb)(°F)	
	Psia p	Psig gp	Liquid v	Vapor V	Liquid h	Vapor H		Liquid s	Vapor S
60	106.9	92.2	0.03150	0.984	239.6	392.2	152.6	1.0511	1.3441
62	110.2	95.5	0.03162	0.958	240.8	392.7	151.8	1.0534	1.3438
64	113.6	98.9	0.03174	0.932	242.0	393.1	151.1	1.0556	1.3435
66	117.1	102.4	0.03185	0.906	243.2	393.5	150.3	1.0579	1.3433
68	120.6	105.9	0.03197	0.880	244.4	394.0	149.5	1.0601	1.3430
70	124.3	109.6	0.03209	0.854	245.7	394.4	148.7	1.0624	1.3427
72	127.9	113.2	0.03221	0.832	246.9	394.8	147.8	1.0647	1.3424
74	131.7	117.0	0.03233	0.810	248.1	395.2	147.0	1.0669	1.3421
76	135.6	120.9	0.03245	0.788	249.4	395.6	146.2	1.0692	1.3419
78	139.6	124.9	0.03257	0.766	250.2	396.0	145.4	1.0714	1.3416
80	143.6	128.9	0.03269	0.745	251.9	396.4	144.5	1.0737	1.3413
82	147.7	133.0	0.03281	0.725	253.1	396.8	143.7	1.0760	1.3410
84	151.8	137.1	0.03293	0.704	254.4	397.2	142.8	1.0782	1.3408
86	156.2	141.5	0.03305	0.684	255.6	397.6	141.9	1.0805	1.3405
88	160.6	145.9	0.03317	0.663	256.9	398.0	141.0	1.0827	1.3403
90	165.0	150.3	0.03329	0.643	258.2	398.3	140.1	1.0850	1.3400
92	169.6	154.9	0.03341	0.626	259.5	398.7	139.2	1.0873	1.3398
94	174.2	159.5	0.03353	0.609	260.8	399.1	138.3	1.0895	1.3395
96	178.9	164.2	0.03366	0.592	262.1	399.5	137.4	1.0918	1.3393
98	183.7	169.0	0.03378	0.575	263.3	399.9	136.5	1.0940	1.3390
100	188.7	174.0	0.03390	0.558	264.6	400.2	135.6	1.0963	1.3388
102	193.8	179.1	0.03402	0.544	265.9	400.5	134.6	1.0986	1.3386
104	198.9	184.2	0.03415	0.530	267.2	400.9	133.7	1.1010	1.3384
106	204.1	189.4	0.03427	0.516	268.5	401.2	132.7	1.1033	1.3382
108	209.3	194.6	0.03439	0.502	269.8	401.6	131.8	1.1057	1.3380
110	214.8	200.1	0.03452	0.487	271.1	401.9	130.8	1.1080	1.3378
112	220.4	205.7	0.03468	0.475	272.5	402.3	129.8	1.1103	1.3376
114	226.0	211.3	0.03484	0.463	273.9	402.7	128.8	1.1126	1.3374
116	231.6	216.9	0.03500	0.451	275.2	403.0	127.8	1.1149	1.3372
118	237.3	222.6	0.03516	0.439	276.6	403.4	126.8	1.1172	1.3370
120	243.4	228.7	0.03532	0.426	278.0	403.8	125.8	1.1195	1.3368
122	249.7	235.0	0.03548	0.415	279.4	404.1	124.7	1.1218	1.3366
124	255.7	241.0	0.03564	0.404	280.9	404.5	123.6	1.1241	1.3363
126	261.7	247.0	0.03580	0.393	282.3	404.8	122.5	1.1264	1.3361
128	267.9	253.2	0.03596	0.382	283.8	405.2	121.4	1.1287	1.3358

TABLE E-16.—THERMODYNAMIC PROPERTIES OF SATURATED PROPANE (*Concluded*)

Temp. t, °F	Pressure		Volume, cu ft/lb		Heat content, Btu/lb		Latent heat L, Btu/lb	Entropy, Btu/(lb)(°F)	
	Psia p	Psig gp	Liquid v	Vapor V	Liquid h	Vapor H		Liquid s	Vapor S
130	274.5	259.8	0.03612	0.370	285.2	405.4	120.2	1.1310	1.3356
132	281.1	266.4	0.03630	0.360	286.7	405.7	119.0	1.1334	1.3353
134	287.9	273.2	0.03648	0.350	288.2	406.1	117.9	1.1358	1.3350
136	294.7	280.0	0.03666	0.340	289.7	406.4	116.7	1.1382	1.3348
138	301.4	286.7	0.03684	0.330	291.2	406.7	115.5	1.1406	1.3345
140	308.4	293.7	0.03702	0.320	292.7	407.0	114.3	1.1430	1.3347
142	315.5	300.8	0.03725	0.312	294.2	407.3	113.1	1.1454	1.3339
144	322.8	308.1	0.03748	0.303	295.7	407.6	111.9	1.1479	1.3336
146	330.2	315.5	0.03771	0.295	297.2	407.8	110.6	1.1503	1.3332
148	337.6	322.9	0.03794	0.286	298.6	408.0	109.4	1.1528	1.3329
150	345.4	330.7	0.03817	0.278	300.2	408.2	108.0	1.1552	1.3326
152	352.9	338.2	0.03846	0.270	301.8	408.4	106.6	1.1578	1.3321
154	360.8	346.1	0.03875	0.263	303.4	408.6	105.2	1.1603	1.3317
156	368.6	353.9	0.03904	0.255	305.1	408.7	103.6	1.1629	1.3312
158	376.6	361.9	0.03933	0.248	306.8	408.8	102.0	1.1654	1.3308
160	385.0	370.3	0.03962	0.240	308.4	408.8	100.4	1.1680	1.3303
162	392.9	378.2	0.03996	0.234	310.2	408.8	98.6	1.1707	1.3297
164	401.0	386.3	0.04030	0.227	312.0	408.9	96.9	1.1734	1.3291
166	409.3	394.6	0.04064	0.221	313.9	408.9	95.0	1.1762	1.3284
168	417.8	403.1	0.04098	0.214	315.7	408.8	93.1	1.1789	1.3278
170	426.0	411.3	0.04132	0.208	317.5	408.6	91.1	1.1816	1.3272
172	463.4	421.7	0.04179	0.202	319.5	408.6	89.1	1.1847	1.3262
174	445.9	431.2	0.04226	0.197	321.5	408.6	87.1	1.1878	1.3252
176	455.2	440.5	0.04273	0.191	323.5	408.4	84.9	1.1908	1.3243
178	464.1	449.4	0.04320	0.186	325.5	408.2	82.7	1.1939	1.3233
180	473.2	458.5	0.04367	0.180	327.5	407.6	80.1	1.1970	1.3223
182	483.0	468.3	0.04436	0.174	329.8	407.4	77.6	1.2004	1.3210
184	492.9	478.2	0.04505	0.168	332.2	407.1	74.9	1.2038	1.3196
186	503.1	488.4	0.04574	0.161	334.5	406.6	72.1	1.2072	1.3183
188	512.8	498.1	0.04643	0.155	336.9	405.9	69.0	1.2106	1.3169
190	523.4	508.7	0.04712	0.149	339.2	404.6	65.7	1.2140	1.3156
200	575.0	560.3	0.0521	0.113	353.5	398.3	44.8	1.2360	1.3040

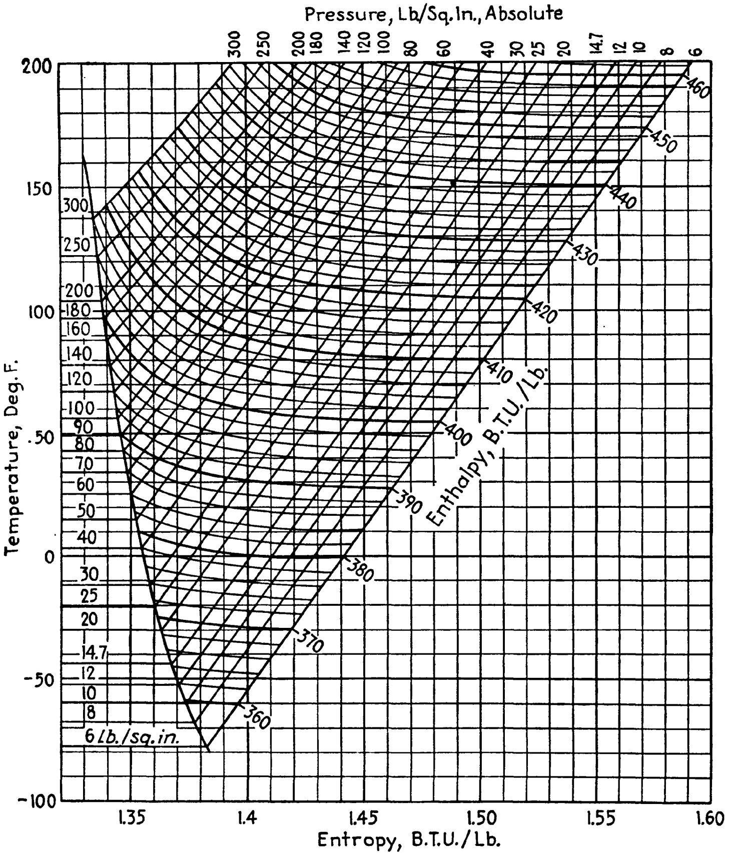

FIG. E-20.—Temperature-entropy chart for propane vapor. [*Stearns and George, Ind. Eng. Chem.* **35**, 602, (1943). *By permission of the American Chemical Society.*]

TABLE E-17.—SATURATED AMMONIA: TEMPERATURE TABLE
[*Bur. Standards Circ.* 142 (1923)]

Temp. t, °F	Pressure		Volume vapor, cu ft/lb	Density vapor, lb/cu ft	Heat content		Latent heat, Btu/lb	Entropy	
	Psia	Psig			Liquid, Btu/lb	Vapor, Btu/lb		Liquid, Btu/(lb)(°F)	Vapor, Btu/(lb)(°F)
	p	gp	V	$1/V$	h	H	L	s	S
−60	5.55	18.6*	44.73	0.02235	−21.2	589.6	610.8	−0.0517	1.4769
−58	5.93	17.8*	42.05	0.02378	−19.1	590.4	609.5	−0.0464	1.4713
−56	6.33	17.0*	39.56	0.02528	−17.0	591.2	608.2	−0.0412	1.4658
−54	6.75	16.2*	37.24	0.02685	−14.8	592.1	606.9	0.0360	1.4604
−52	7.20	15.3*	35.09	0.02850	−12.7	592.9	605.6	−0.0307	1.4551
−50	7.67	14.3*	33.08	0.03023	−10.6	593.7	604.3	−0.0256	1.4497
−48	8.16	13.3*	31.20	0.03205	− 8.5	594.4	602.9	−0.0204	1.4445
−46	8.68	12.2*	29.45	0.03395	− 6.4	595.2	601.6	−0.0153	1.4393
−44	9.23	11.1*	27.82	0.03595	− 4.3	596.0	600.3	−0.0102	1.4342
−42	9.81	10.0*	26.29	0.03804	− 2.1	596.8	598.9	−0.0051	1.4292
−40	10.41	8.7*	24.86	0.04022	0.0	597.6	597.6	0.0000	1.4242
−38	11.04	7.4*	23.53	0.04251	2.1	598.3	596.2	0.0051	1.4193
−36	11.71	6.1*	22.27	0.04489	4.3	599.1	594.8	0.0101	1.4144
−34	12.41	4.7*	21.10	0.04739	6.4	599.9	593.5	0.0151	1.4096
−32	13.14	3.2*	20.00	0.04999	8.5	600.6	592.1	0.0201	1.4048
−30	13.90	1.6*	18.97	0.05271	10.7	601.4	590.7	0.0250	1.4001
−28	14.71	0.0	18.00	0.05555	12.8	602.1	589.3	0.0300	1.3955
−26	15.55	0.8	17.09	0.05850	14.9	602.8	587.9	0.0350	1.3909
−24	16.42	1.7	16.24	0.06158	17.1	603.6	586.5	0.0399	1.3863
−22	17.34	2.6	15.43	0.06479	19.2	604.3	585.1	0.0448	1.3818
−20	18.30	3.6	14.68	0.06813	21.4	605.0	583.6	0.0497	1.3774
−18	19.30	4.6	13.97	0.07161	23.5	605.7	582.2	0.0545	1.3729
−16	20.34	5.6	13.29	0.07522	25.6	606.4	580.8	0.0594	1.3686
−14	21.43	6.7	12.66	0.07898	27.8	607.1	579.3	0.0642	1.3643
−12	22.56	7.9	12.06	0.08289	30.0	607.8	577.8	0.0690	1.3600
−10	23.74	9.0	11.50	0.08695	32.1	608.5	576.4	0.0738	1.3558
− 8	24.97	10.3	10.97	0.09117	34.3	609.2	574.9	0.0786	1.3516
− 6	26.26	11.6	10.47	0.09555	36.4	609.8	573.4	0.0833	1.3474
− 4	27.59	12.9	9.991	0.1001	38.6	610.5	571.9	0.0880	1.3433
− 2	28.98	14.3	9.541	0.1048	40.7	611.1	570.4	0.0928	1.3393

* Inches of mercury below 1 standard atmosphere (29.92 in.).

TABLE E-17.—SATURATED AMMONIA: TEMPERATURE TABLE (*Continued*)

Temp. *t*, °F	Pressure		Volume vapor, cu ft/lb	Density vapor, lb/cu ft	Heat content		Latent heat, Btu/lb	Entropy	
	Psia	Psig			Liquid, Btu/lb	Vapor, Btu/lb		Liquid, Btu/(lb)(°F)	Vapor, Btu/(lb)(°F)
	p	*gp*	*V*	1/*V*	*h*	*H*	*L*	*s*	*S*
0	30.42	15.7	9.116	0.1097	42.9	611.8	568.9	0.0975	1.3352
2	31.92	17.2	8.714	0.1148	45.1	612.4	567.3	0.1022	1.3312
4	33.47	18.8	8.333	0.1200	47.2	613.0	565.8	0.1069	1.3273
6	35.09	20.4	7.971	0.1254	49.4	613.6	564.2	0.1115	1.3234
8	36.77	22.1	7.629	0.1311	51.6	614.3	562.7	0.1162	1.3195
10	38.51	23.8	7.304	0.1369	53.8	614.9	561.1	0.1208	1.3157
12	40.31	25.6	6.996	0.1429	56.0	615.5	559.5	0.1254	1.3118
14	42.18	27.5	6.703	0.1492	58.2	616.1	557.9	0.1300	1.3081
16	44.12	29.4	6.425	0.1556	60.3	616.6	556.3	0.1346	1.3043
18	46.13	31.4	6.161	0.1623	62.5	617.2	554.7	0.1392	1.3006
20	48.21	33.5	5.910	0.1692	64.7	617.8	553.1	0.1437	1.2969
22	50.36	35.7	5.671	0.1763	66.9	618.3	551.4	0.1483	1.2933
24	52.59	37.9	5.443	0 1837	69.1	618.9	549.8	0.1528	1.2897
26	54.90	40.2	5.227	0.1913	71.3	619.4	548.1	0 1573	1.2861
28	57.28	42.6	5.021	0.1992	73.5	619.9	546.4	0.1618	1.2825
30	59.74	45.0	4.825	0.2073	75.7	620.5	544.8	0.1663	1.2790
32	62.29	47.6	4.637	0.2156	77.9	621.0	543.1	0.1708	1.2755
34	64.91	50.2	4.459	0.2243	80.1	621.5	541.4	0.1753	1.2721
36	67.63	52.9	4.289	0.2332	82.3	622.0	539.7	0.1797	1.2686
38	70.43	55.7	4.126	0.2423	84.6	622.5	537.9	0.1841	1.2652
40	73.32	58.6	3.971	0.2518	86.8	623.0	536.2	0.1885	1.2618
42	76.31	61.6	3.823	0.2616	89.0	623.4	534.4	0.1930	1.2585
44	79.38	64.7	3.682	0.2716	91.2	623.9	532.7	0.1974	1.2552
46	82.55	67.9	3.547	0.2819	93.5	624.4	530.9	0.2018	1.2519
48	85.82	71.1	3.418	0.2926	95.7	624.8	529.1	0.2062	1.2486
50	89.19	74.5	3.294	0.3036	97.9	625.2	527.3	0.2105	1.2453
52	92.66	78.0	3.176	0.3149	100.2	625.7	525.5	0.2149	1.2421
54	96.23	81.5	3.063	0.3265	102.4	626.1	523.7	0.2192	1.2389
56	99.91	85.2	2.954	0.3385	104.7	626.5	521.8	0.2236	1.2357
58	103.7	89.0	2.851	0.3508	106.9	626.9	520.0	0.2279	1.2325
60	107.6	92.9	2.751	0.3635	109.2	627.3	518.1	0.2322	1.2294
62	111.6	96.9	2.656	0.3765	111.5	627.7	516.2	0.2365	1.2262
64	115.7	101.0	2.565	0.3899	113.7	628.0	514.3	0.2408	1.2231
66	120.0	105.3	2.477	0.4037	116.0	628.4	512.4	0.2451	1.2201
68	124.3	109.6	2.393	0.4179	118.3	628.8	510.5	0.2494	1.2170

Table E-17.—Saturated Ammonia: Temperature Table (*Concluded*)

Temp. t, °F	Pressure		Volume vapor, cu ft/lb	Density vapor, lb/cu ft	Heat content		Latent heat, Btu/lb	Entropy	
	Psia	Psig			Liquid, Btu/lb	Vapor, Btu/lb		Liquid, Btu/(lb)(°F)	Vapor, Btu/(lb)(°F)
	p	gp	V	$1/V$	h	H	L	s	S
70	128.8	114.1	2.312	0.4325	120.5	629.1	508.6	0.2537	1.2140
72	133.4	118.7	2.235	0.4474	122.8	629.4	506.6	0.2579	1.2110
74	138.1	123.4	2.161	0.4628	125.1	629.8	504.7	0.2622	1.2080
76	143.0	128.3	2.089	0.4786	127.4	630.1	502.7	0.2664	1.2050
78	147.9	133.2	2.021	0.4949	129.7	630.4	500.7	0.2706	1.2020
80	153.0	138.3	1.955	0.5115	132.0	630.7	498.7	0.2749	1.1991
82	158.3	143.6	1.892	0.5287	134.3	631.0	496.7	0.2791	1.1962
84	163.7	149.0	1.831	0.5462	136.6	631.3	494.7	0.2833	1.1933
86	169.2	154.5	1.772	0.5643	138.9	631.5	492.6	0.2875	1.1904
88	174.8	160.1	1.716	0.5828	141.2	631.8	490.6	0.2917	1.1875
90	180.6	165.9	1.661	0.6019	143.5	632.0	488.5	0.2958	1.1846
92	186.6	171.9	1.609	0.6214	145.8	632.2	486.4	0.3000	1.1818
94	192.7	178.0	1.559	0.6415	148.2	632.5	484.3	0.3041	1.1789
96	198.9	184.2	1.510	0.6620	150.5	632.6	482.1	0.3083	1.1761
98	205.3	190.6	1.464	0.6832	152.9	632.9	480.0	0.3125	1.1733
100	211.9	197.2	1.419	0.7048	155.2	633.0	477.8	0.3166	1.1705
102	218.6	203.9	1.375	0.7270	157.6	633.2	475.6	0.3207	1.1677
104	225.4	210.7	1.334	0.7498	159.9	633.4	473.5	0.3248	1.1649
106	232.5	217.8	1.293	0.7732	162.3	633.5	471.2	0.3289	1.1621
108	239.7	225.0	1.254	0.7972	164.6	633.6	469.0	0.3330	1.1593
110	247.0	232.3	1.217	0.8219	167.0	633.7	466.7	0.3372	1.1566
112	254.5	239.8	1.180	0.8471	169.4	633.8	464.4	0.3413	1.1538
114	262.2	247.5	1.145	0.8730	171.8	633.9	462.1	0.3453	1.1510
116	270.1	255.4	1.112	0.8996	174.2	634.0	459.8	0.3495	1.1483
118	278.2	263.5	1.079	0.9269	176.6	634.0	457.4	0.3535	1.1455
120	286.4	271.7	1.047	0.9549	179.0	634.0	455.0	0.3576	1.1427
122	294.8	280.1	1.017	0.9837	181.4	634.0	452.6	0.3618	1.1400
124	303.4	288.7	0.987	1.0132	183.9	634.0	450.1	0.3659	1.1372
125	307.8	293.1	0.973	1.028	185.1	634.0	448.9	0.3679	1.1358

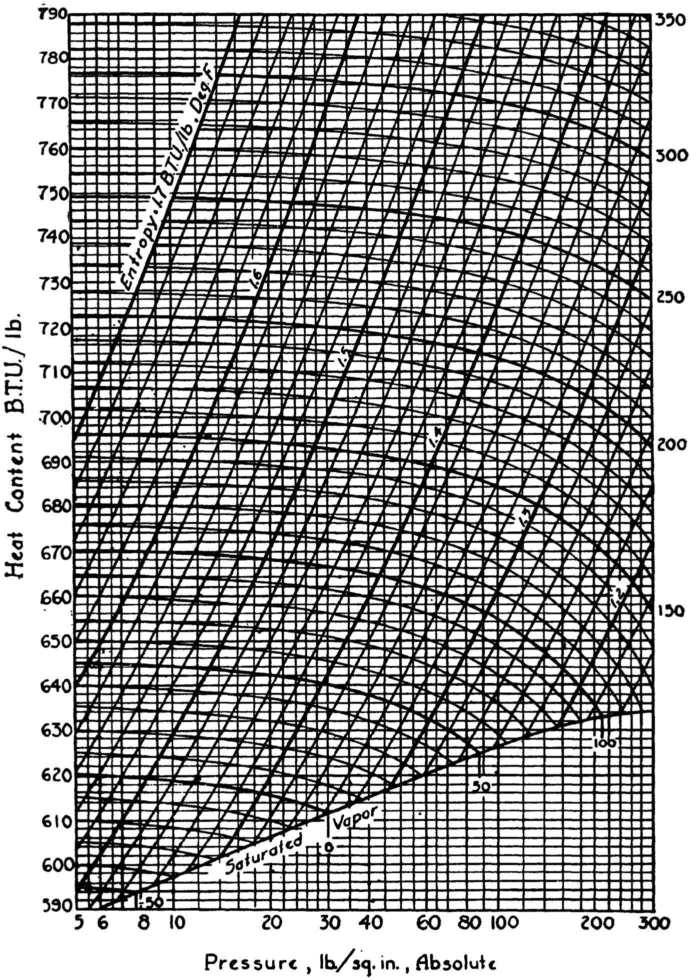

FIG. E-21.—Thermodynamic chart for ammonia vapor. [*Nat. Bur. Stand. Circ. No.* 142 (1923).]

TABLE E-18.—CARBON DIOXIDE (CO_2), SATURATED VAPOR*

(Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York, 1941)

Temp. °F	Pressure			Volume		Density		Heat content above 32°F			Entropy from 32°F		
	Psia	Psig	Atm, gauge	Liquid, cu ft/lb	Vapor, cu ft/lb	Liquid, lb/cu ft	Vapor, lb/cu ft	Liquid, Btu/lb	Latent, Btu/lb	Vapor, Btu/lb	Liquid, Btu/(lb) (°F)	Evapor., Btu/(lb) (°F)	Vapor, Btu/(lb) (°F)
−20	220.6	205.9	14.00	0.0155	0.4166	64.34	2.401	−23.96	126.0	102.0	−0.0514	0.2867	0.2353
−18	228.4	213.7	14.53	0.0156	0.4018	64.15	2.489	−23.13	125.2	102.1	−0.0495	0.2837	0.2342
−16	236.4	221.7	15.08	0.0156	0.3876	63.94	2.580	−22.30	124.5	102.2	−0.0476	0.2807	0.2331
−14	244.6	229.9	15.64	0.0157	0.3739	63.73	2.674	−21.46	123.7	102.2	−0.0458	0.2777	0.2319
−12	253.0	238.3	16.21	0.0157	0.3608	63.49	2.772	−20.61	122.9	102.3	−0.0439	0.2746	0.2307
−10	261.7	247.0	16.80	0.0158	0.3482	63.25	2.872	−19.76	122.0	102.3	−0.0420	0.2716	0.2296
− 8	270.6	255.9	17.41	0.0159	0.3360	63.01	2.976	−18.90	121.2	102.3	−0.0401	0.2685	0.2284
− 6	279.7	265.0	18.03	0.0159	0.3243	62.76	3.083	−18.04	120.3	102.3	−0.0382	0.2654	0.2273
− 4	289.1	274.4	18.67	0.0160	0.3131	62.50	3.194	−17.17	119.5	102.3	−0.0362	0.2623	0.2261
− 2	298.7	284.0	19.32	0.0161	0.3022	62.23	3.309	−16.29	118.6	102.3	−0.0343	0.2592	0.2249
0	308.6	293.9	20.00	0.0161	0.2918	61.95	3.427	−15.41	117.7	102.2	−0.0324	0.2561	0.2237
2	318.7	304.0	20.68	0.0162	0.2817	61.65	3.550	−14.51	116.7	102.2	−0.0304	0.2530	0.2225
4	329.1	314.4	21.39	0.0163	0.2720	61.36	3.676	−13.61	115.8	102.1	−0.0285	0.2498	0.2213
5	334.4	319.7	21.75	0.0163	0.2673	61.22	3.741	−13.16	115.3	102.1	−0.0275	0.2482	0.2207
6	339.8	325.1	22.11	0.0164	0.2627	61.07	3.807	−12.71	114.8	102.1	−0.0266	0.2466	0.2201
8	350.7	336.0	22.85	0.0165	0.2537	60.77	3.942	−11.79	113.8	102.0	−0.0246	0.2435	0.2189
10	361.8	347.1	23.61	0.0165	0.2450	60.48	4.082	−10.87	112.8	101.9	−0.0226	0.2402	0.2176
12	373.3	358.6	24.39	0.0166	0.2366	60.18	4.227	− 9.934	111.7	101.8	−0.0206	0.2370	0.2164
16	397.1	382.4	26.01	0.0168	0.2207	59.58	4.532	− 8.038	109.6	101.5	−0.0166	0.2305	0.2139
25	454.8	440.1	29.94	0.0172	0.1886	58.14	5.303	− 3.618	104.3	100.7	−0.0074	0.2154	0.2080
35	526.4	511.7	34.81	0.0177	0.1581	56.41	6.323	1.604	97.77	99.38	0.0033	0.1978	0.2010
45	606.5	591.8	40.26	0.0184	0.1321	54.41	7.571	7.251	90.21	97.46	0.0146	0.1788	0.1934
55	695.9	681.2	46.34	0.0192	0.1095	52.05	9.132	13.40	81.29	94.78	0.0268	0.1580	0.1849
65	795.1	780.4	53.09	0.0203	0.0894	49.14	11.18	20.66	70.35	91.01	0.0406	0.1342	0.1748
75	905.1	890.4	60.57	0.0222	0.0708	45.05	14.13	29.50	55.83	85.33	0.0573	0.1045	0.1618
85	1027.0	1012.3	68.83	0.0258	0.0500	38.76	20.00	43.18	31.29	74.47	0.0826	0.0575	0.1401
86	1039.0	1024.3	69.70	0.0267	0.0474	37.41	21.09	45.45	27.00	72.46	0.0868	0.0495	0.1363
88.43	1071.0	1056.3	71.86	0.0346	0.0346	28.90	28.90	59.23	0.00	59.23	0.1120	0.0000	0.1120

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* Mollier (Amagat), Hodson, "Ice and Cold Storage," London, 1914. Rearranged to conform to A.S.R.E. Standard. *Am. Soc. Refrig. Eng. Circ.* 9 (1926).

6. Heats of Reaction

a. Heats of Formation.—Heats of reaction are conveniently summarized in tabular form by the heats of formation from the elements. The heat of formation of a compound is usually defined as the heat that would be absorbed by the spontaneous formation of 1 mole of that substance from the elements when the reaction is conducted at 18°C (64.4°F) and atmospheric pressure. Actually, of course, very few substances may be so formed, and most heats of formation are, therefore, determined indirectly. Heats of formation are frequently given at 25°C (77°F) instead of 18°C.

Heats of formation for a few inorganic substances are given in Table E-19; for hydrocarbons, in Table E-20. For additional heats of formation the reader is referred to reference texts, particularly Bichowsky and Rossini.[1]

The procedure used in employing these heats of formation is illustrated by Example E-2, the computation of the heat of solution of carbon dioxide in sodium hydroxide.

Example E-2. Compute the heat of solution of carbon dioxide in sodium hydroxide solution (1 mole dissolved in 400 moles of water, *i.e.*, 0.55 per cent NaOH) to form sodium carbonate solution (1 mole dissolved in 401 moles of water).

Reaction,

$$CO_2(g) + 2NaOH(aq, 400) = Na_2CO_3(aq, 401) + H_2O(l)$$

Heat of formation of products,

$Na_2CO_3(aq, 400)\Delta H°$	−495,200 Btu/lb mole
$H_2O(l)\Delta H°$	−123,070 Btu/lb mole
Total	−618,270

Heat of formation of reactants,

$CO_2(g)\Delta H°$	−169,300 Btu/lb mole
$2NaOH(aq, 400)\Delta H° = -2 \times 201{,}700$	−403,400 Btu/two lb moles
Total	−572,700

$$\text{Change in heat content} = \Delta H = -618{,}270 + 572{,}700 = -45{,}570$$

$$\text{Heat of reaction} = -\Delta H = 45{,}570 \text{ Btu/lb mole of } CO_2$$

This is the heat of solution of 1 mole of carbon dioxide in 0.55 per cent sodium hydroxide to form a solution of sodium carbonate.

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[1] "Thermochemistry of the Chemical Substances," Reinhold Publishing Corporation, New York, 1938.

TABLE E-19.—HEATS OF FORMATION OF A FEW INORGANIC SUBSTANCES (Abstracted from Bichowsky and Rossini, "Thermochemistry of the Chemical Substances," Reinhold Publishing Corporation, New York, 1936, except as otherwise noted)

Substance, formula, and state*	Heat of formation at 18°C (64.4°F) from elements	
	Kg-cal/g mole	Btu/lb mole
Aluminum:		
Metal, Al (*s*)	0.00†	0†
Chloride, $AlCl_3$ (*s*)	−166.8	−300,200
$AlCl_3$ (*aq*, 600)	−244.7	−440,500
Oxide Al_2O_3 (*s*)	−380	−684,000
Calcium:		
Metal, Ca (*s*)	0.00†	0†
Carbide, CaC_2 (*s*)	−14.5	−26,100
Chloride, $CaCl_2$ (*s*)	−190.6	−343,100
$CaCl_2$ (*aq*)	−208.69	−375,600
Carbonate, $CaCO_3$ (*s*)	−289.1	−520,400
Oxide, CaO (*s*)	−151.7	−273,100
Hydroxide, $Ca(OH)_2$ (*s*)	−236.0	−424,800
Sulphate, $CaSO_4$ (*s*)	−340.7	−613,300
Carbon compounds:		
Graphite, C (*s*)	0.00†	0†
Methyl alcohol, CH_3OH (*l*)	−57.02	−102,600
Ethyl alcohol, C_2H_5OH (*l*)	−66.28	−119,300
Carbon monoxide, CO (*g*)	−26.39‡	−47,500‡
Carbon dioxide, CO_2 (*g*)	−94.03	−169,300
Carbon disulphide, CS_2 (*g*)	22	39,600
Chlorine, Cl_2 (*g*)	0.00†	0†
Hydrogen compounds:		
Element, H_2 (*g*)	0.00†	0†
Hydrogen chloride, HCl (*g*)	−22.06	−39,700
HCl (*aq*, 400)	−39.53	−71,100
Hydrogen cyanide, HCN (*g*)	31.1	56,000
HCN (*aq*, 100)	24.3	43,700
Formic acid, HCOOH (*l*)	−99.6	−179,300
HCOOH (*aq*, 200)	−99.76	−179,600
Nitric acid, HNO_3 (*l*)	−41.66	−75,000
HNO_3 (*aq*, 400)	−49.11	−88,400
Water, H_2O (*l*)	−68.372‡	−123,070‡
H_2O (*g*)	−57.781‡	−104,010‡
Phosphoric acid, H_3PO_4 (*s*)	−303.37	−546,100
H_3PO_4 (*aq*, 400)	−306.16	−551,100
Hydrogen sulphide, H_2S (*g*)	−4.80	−8,650
Sulphuric acid, H_2SO_4 (*l*)	−193.75	−348,750
H_2SO_4 (*aq*, 400)	−211.84	−381,300

* Symbol in parentheses indicates state, see end of table.

† By definition.

‡ Based on values of Rossini, *J. Research, Nat. Bur. Standards*, **22**, 407 (1939) corrected to 18°C.

TABLE E-19.—HEATS OF FORMATION OF A FEW INORGANIC SUBSTANCES (*Continued*)

Substance, formula, and state*	Heat of formation at 18°C (64.4°F) from elements	
	Kg-cal/g mole	Btu/lb mole
Iron compounds:		
Metal, Fe (*α*)	0.00†	0†
Ferrous chloride, $FeCl_2$ (*s*)	−81.9	−147,400
$FeCl_2$ (*aq*)	−99.8	−179,600
Ferric chloride, $FeCl_3$ (*s*)	−96.4	−173,400
$FeCl_3$ (*aq*, 1,000)	−128.1	−230,600
Ferric oxide, Fe_2O_3 (*s*)	−198.5	−357,300
Magnetic oxide, Fe_3O_4 (*s*)	−266.9	−480,400
Magnesium:		
Metal, Mg (*s*)	0.00†	0†
Chloride, $MgCl_2$ (*s*)	−151.6	−272,900
$MgCl_2$ (*aq*, 400)	−189.13	−340,400
Oxide, MgO (*s*)	−146.1	−263,000
Sulphate, $MgSO_4$ (*s*)	−304.95	−548,900
$MgSO_4$ (*aq*, 400)	−325.25	−585,400
Nitrogen compounds:		
Element, N_2 (*g*)	0.00†	0†
Ammonia, NH_3 (*g*)	−11.00	−19,800
NH_3 (*aq*, 200)	−19.35	−34,800
Ammonium chloride, NH_4Cl (*s*)	−74.95	−134,900
NH_4Cl (*aq*, 400)	−71.06	−127,900
Oxygen, O_2 (*g*)	0.00†	0†
Potassium:		
Metal, K (*s*)	0.00†	0†
Chloride, KCl (*s*)	−104.361	−187,850
KCl (*aq*, 400)	−99.899	−179,820
Carbonate, K_2CO_3 (*s*)	−274.03	−493,300
K_2CO_3 (*aq*, 400)	−280.66	−505,200
Hydroxide, KOH (*s*)	−102.02	−183,600
KOH (*aq*, 400)	−114.82	−206,700
Sulphate, K_2SO_4 (*s*)	−342.66	−616,800
K_2SO_4 (*aq*, 400)	−336.24	−605,200
Sodium:		
Metal, Na (*s*)	0.00†	0†
Chloride, NaCl (*s*)	−98.330	−176,900
NaCl (*aq*, 400)	−97.105	−174,790
Cyanide, NaCN (*s*)	−22.52	−40,500
NaCN (*aq*, 200)	−22.15	−39,900
Carbonate, Na_2CO_3 (*s*)	−269.46	−485,100
Na_2CO_3 (*aq*, 400)	−275.09	−495,200
Bicarbonate, $NaHCO_3$ (*s*)	−226.0	−406,800
$NaHCO_3$ (*aq*)	−221.9	−399,400

* Symbol in parentheses indicates state, see end of table.

† By definition.

TABLE E-19.—HEATS OF FORMATION OF A FEW INORGANIC SUBSTANCES (*Concluded*)

Substance, formula, and state*	Heat of formation at 18°C (64.4°F) from elements	
	Kg-cal/g mole	Btu/lb mole
Sodium: *Continued*		
Nitrate, $NaNO_3$ (*s*)	−111.72	−201,100
$NaNO_3$ (*aq*, 400)	−106.684	−192,000
Hydroxide, NaOH (*s*)	−101.96	−183,500
NaOH (*aq*, 400)	−112.053	−201,700
Sulphide, Na_2S (*s*)	− 89.8	−161,600
Na_2S (*aq*, 400)	−104.96	−188,900
Sulphate, Na_2SO_4 (*s*)	−330.48	−594,900
Na_2SO_4 (*aq*, 400)	−330.735	−595,300
Sulphur:		
Rhombic S (*s*)	0.00†	0†
Dioxide, SO_2 (*g*)	− 70.92	127,700
Trioxide, SO_3 (*g*)	− 93.9	169,000

* Symbol in parentheses indicates state.

(*s*) denotes solid; (*g*) gas; (*l*) liquid; (*α*) crystal form; (*aq*) dilute water solution; and (*aq*, 400) solution 1 mole in 400 moles of water.

† By definition.

The heats of reaction computed by this method are precise, provided the reactants and products are at the standard conditions specified. If high pressures or concentrated solutions are involved, corrections may be necessary.

Very often a heat of reaction may be desired at temperatures other than 64.4°F. In this case correction is necessary but may be readily made from specific heat data by use of Hess' law of constant heat summation. This law states that the heat of reaction is independent of the manner in which it is conducted and depends only on the initial and final states.

If the heat of reaction is desired at some temperature, T, it may be computed in three steps: (1) Compute the heat change, ΔH_1, required to heat or cool the reactants to 64.4°F. (2) Compute the heat change accompanying reaction ΔH_2 at 64.4°F from the heats of formation. (3) Compute the heat change, ΔH_3, required to restore the reaction products to T, the initial temperature. The heat of reaction, $-\Delta H$, will then be obtained by securing the algebraic sum

$$(\Delta H = \Delta H_1 + \Delta H_2 + \Delta H_3)$$

TABLE E-20.—HEATS OF FORMATION OF GASEOUS HYDROCARBONS FROM CARBON (GRAPHITE) AND GASEOUS HYDROGEN AT 25°C (77°F)
[Abstracted from Rossini, *Chem. Rev.*, **27**, 1 (1940), published by The Williams & Wilkins Company, Baltimore, Md.]

Substance	Heat of formation	
	Cal/g mole	Btu/lb mole
Methane, CH_4 (*g*)	−17,865 ± 74	−32,157
Acetylene, C_2H_2 (*g*)	54,228 ± 235	97,610
Ethylene, C_2H_4 (*g*)	12,556 ± 67	22,601
Ethane, C_2H_6 (*g*)	−20,191 ± 108	−36,344
Propylene, C_3H_6 (*g*)	4,956 ± 110	8,921
Propane, C_3H_8 (*g*)	−24,750 ± 124	−44,550
1-3, Butadiene, C_4H_6 (*g*)	26,865 ± 240	48,357
Isobutylene, C_4H_8 (*g*)	− 3,205 ± 125	− 5,769
1-Butylene, C_4H_8 (*g*)	383 ± 180	689
cis-2-Butylene, C_4H_8 (*g*)	− 1,388 ± 180	− 2,500
trans-2-Butylene, C_4H_8 (*g*)	− 2,338 ± 180	− 4,208
Isobutane, C_4H_{10} (*g*)	−31,350 ± 132	−56,430
n-Butane, C_4H_{10} (*g*)	−29,715 ± 153	−53,487
n-Pentane, C_5H_{12} (*g*)	−34,739 ± 213	−62,530

and reversing the sign. The procedure is illustrated by Example E-3.

Example E-3. Compute the heat of the reaction:

$$C(s) + CO_2(g) = 2CO(g) \text{ at } 1500°F$$

SOLUTION:

1. Cooling C(*s*) from 1500 to 64.4°F,

$$\Delta H = \frac{4.4}{40} 8 - 506 = -505 \text{ Btu/lb}$$
$$= -12 \times 505 = -6060 \text{ Btu/lb mole}$$

(Data from Table E-4)

2. Cooling $CO_2(g)$ from 1500 to 64.4°F,

$$\Delta H = 0.1 - 45.7 = -45.6 \text{ Btu/SCF}$$
$$= -45.6 \times 378.7 = -17{,}300 \text{ Btu/lb mole}$$

(Data from Figs. E-10 and E-11)

3. Total change in heat content for cooling reactants,

$$\Delta H_1 = -6060 - 17{,}300 = -23{,}360 \text{ Btu}$$

4. Reaction at 64.4°F,

Products, $2CO(g)$: $\Delta H^\circ = +2 \times (-47{,}500)$...	$-95{,}000$ Btu
Reactants, $C(s) + CO_2(g)$: $\Delta H^\circ = 0 - 169{,}300$	$-169{,}300$ Btu
Subtracting, ΔH_2........................	$74{,}300$ Btu

5. Heating CO product from 64.4 to 1500°F,

$$\Delta H = 29.3 - 0.1 = 29.2 \text{ Btu/SCF}$$
$$\Delta H_3 = 2 \times 378.7 \times 29.2 = 22{,}100 \text{ Btu}$$

6. Reaction at 1500°F,

$$\Delta H = \Delta H_1 + \Delta H_2 + \Delta H_3 = -23{,}360 + 22{,}100 + 74{,}300 = 73{,}040 \text{ Btu}$$

7. Heat of reaction at 1500°F,

$$-\Delta H = -73{,}040 \text{ Btu}$$

b. Heat of Combustion.—For combustible materials and combustion products (water, carbon dioxide, sulphur dioxide), the heats of combustion may be used for computation of heats of reaction as if they were the heats of formation. That is, the heat of reaction, $-\Delta H$ is the heat of combustion of the reactants less the heat of combustion of the products. Either the gross or net heating values may be so employed. However, if water is one of the reactants or products, the gross value must be used; conversely, if water vapor is involved, the net heat must be employed. Numerical values and definitions of heating values are discussed under Fuels in Chapter H.

7. Heat Balances

The principle of heat balance is the conservation of energy; roughly stated "energy in = energy out." This principle is used in nearly all process calculations of steam, power, and cooling water requirements. The term "heat balance" is usually reserved for calculations made in a formal manner. (The term "heat balance" is used by common consent because heat is usually the predominate item; however, it is really the energy that is balanced.) There are many systems of computing the Btu's in and out. One such system of bookkeeping for a flowing system maintained at steady temperatures and pressures is roughly indicated below.

Heat input includes

1. Heat content (relative to same standard temperature and pressure) of all materials entering system.

2. Heat of reactions taking place in system (heat computed at standard temperature and pressure used in 1).

3. Heat supplied by steam, fuel, etc
4. Work done on system—compression pumping, etc.

(1 hp-hr = 2544 Btu; 1 watt-hour = 3.345 Btu)

5. Kinetic energy of materials entering system,

$$E_K = \frac{Wv^2}{50{,}000}$$

where E_K = kinetic energy, Btu/hr
W = mass of flowing material, lb/hr
v = velocity, fps

6. Potential energy of all materials entering system relative to some fixed height (datum plane) such as the lowest point of system.

Heat output includes

1. Heat content of all materials leaving the system.
2. Work done by system—expansion engines, etc.
3. Heat leaks to atmosphere.
4. Heat removed by cooling water or refrigeration.
5. Kinetic energy of all materials leaving.
6. Potential energy of all materials leaving.

Other items may have to be included in special cases. Frequently, different systems of accounting will be found more suitable. For example, in cracking units a large number of reactions proceed simultaneously and make direct computation difficult. However, the net effect of heats of all reactions may be taken care of by including the heat of formation of materials charged in "heat in" and the heat of formation of materials leaving in "heat out." If only combustible materials and their combustion products are handled, the heat of combustion may be used in place of the heat of formation.

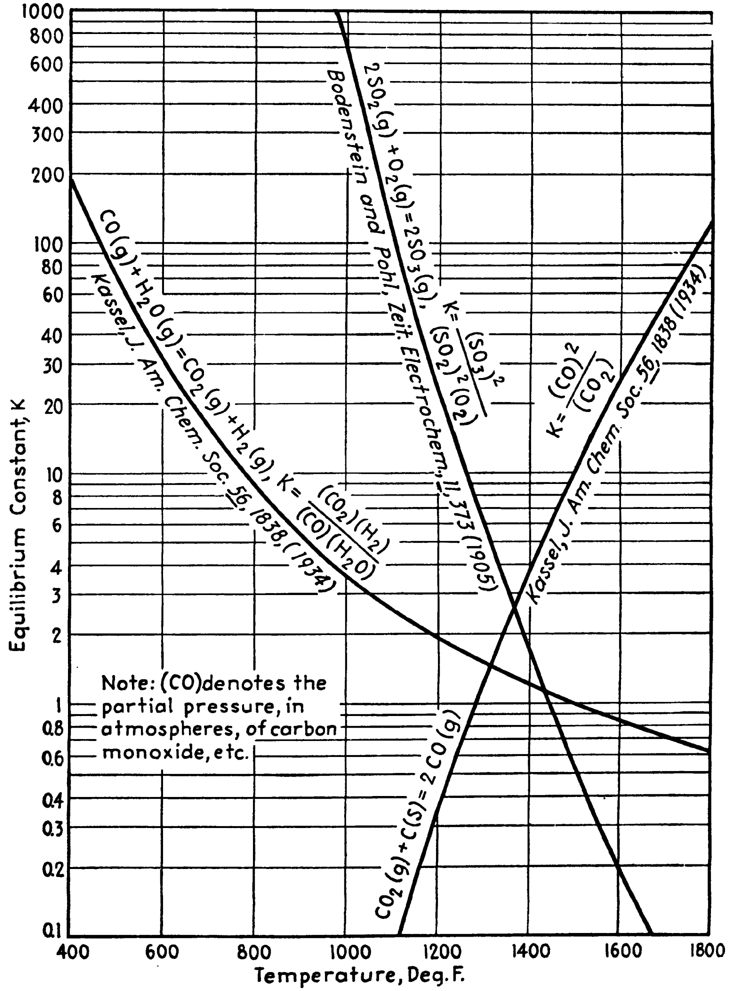
8. Equilibrium Data and Free Energies

Vapor-pressure data have been given earlier in the chapter and a small amount of gas-solubility data and distillation equilibria are given in Chapter L.

Equilibrium of a chemical reaction is usually expressed as the equilibrium constant. The equilibrium constants for three reactions are given in Fig. E-22. These are only examples of the many industrially important equilibria. Much of the equilibrium data is summarized by free energies. The equilibrium constant and free energies are defined in the next section on basic equations. The relation between free energy and the equilibrium constant is given below.

$$-\frac{\Delta F}{T} = R \ln K = 4.577 \log K \qquad \text{(E-18)}$$

where ΔF = change in free energy accompanying reaction (for the number of moles indicated by the reaction equation)
K = equilibrium constant for reaction
T = absolute temperature
R = gas-law constant, same units as $\Delta F/T$
$R \ln K$ = 4.577 log K when $\Delta F/T$ is in cal/(g moles)(°K) or in Btu/(lb moles)(°R)



Note: (CO) denotes the partial pressure, in atmospheres, of carbon monoxide, etc.

Fig. E-22.—Temperature dependence of three equilibrium constants.

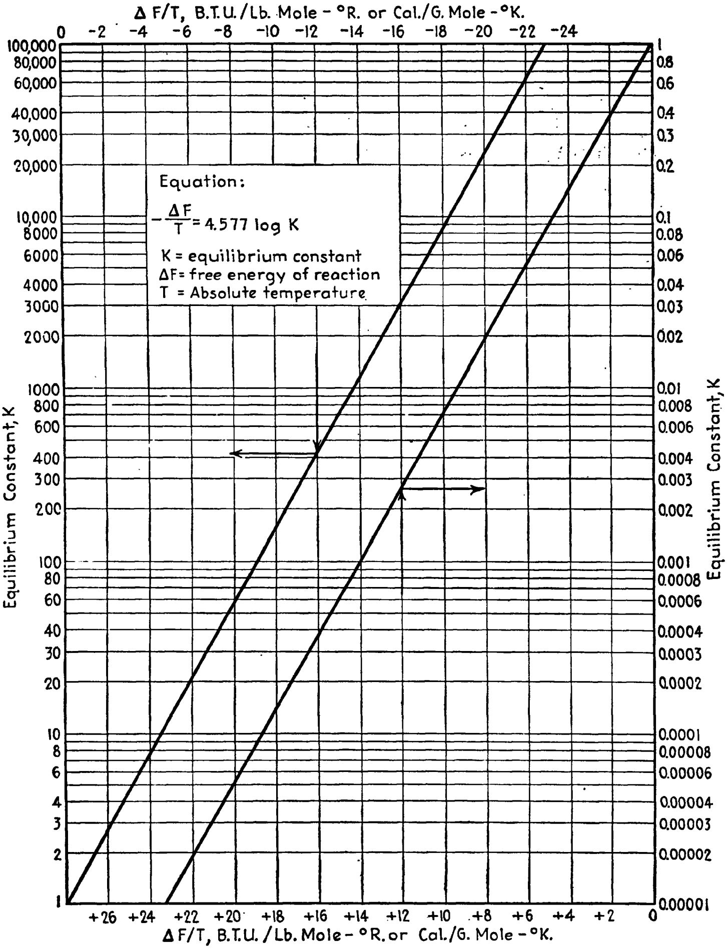


FIG. E-23.—Chart for computing equilibrium constants from free energies.

Figure E-23 may be used instead of Eq. (E-18). The accuracy is low, but possibility of large error is reduced, and the reader who makes many such computations may prepare a chart of larger scale on semilogarithmic paper.

As free energies represent a large specialized field, it would be difficult to give any adequate tabulation here. Fortunately this is not necessary as there are available several excellent tabulations. Free energies of inorganic compounds are given by Latimer.[1] Kelley has summarized data on sulphur compounds,[2] nitrides and carbides,[3] and metal carbonates.[4] Parks and Huffman[5] give extensive data on organic compounds. Data on hydrocarbons are given by Pitzer[6] and by Thacker, Folkins, and Miller.[7]

The use of free-energy data is illustrated by Example E-4.

Example E-4. Compute the equilibrium constant for the reaction $CH_4(g) + H_2O(g) = CO(g) + 3H_2(g)$ at 1700°F (1200°K), and find the amount of conversion achieved when 2 moles of steam per mole of methane are reacted at 1 atm.

SOLUTION: Free-energy data from literature

1. Free energy of formation of products,

$$\begin{aligned} CO: \Delta F^\circ/T &= -43.63 \text{ Btu/(lb mole)(°R)} \\ 3H_2: \Delta F^\circ/T &= \underline{0.00} \\ \text{Total} &= -43.63 \end{aligned}$$

2. Free energy of formation of reactants,

$$\begin{aligned} CH_4: \Delta F^\circ/T &= 8.14 \text{ Btu/(lb mole)(°R)} \\ H_2O: \Delta F^\circ/T &= \underline{-36.15} \\ \text{Total} &= -28.01 \end{aligned}$$

3. Free energy of reaction,

$$\Delta F^\circ/T = -43.63 - (-28.01) = -15.62$$

4. Equilibrium constant,

$$\log K = \frac{1}{4.577} \times \frac{-\Delta F}{T} = \frac{15.62}{4.577} = 3.410$$

$$K = 2{,}570 = \frac{(CO)(H_2)^3}{(CH_4)(H_2O)}$$

5. Methane conversion,

Trial assumption, conversion is nearly complete.
After reaction of 100 moles CH_4 + 200 moles H_2O,
Moles $CH_4 = y$ (to be computed)

---

[1] "Oxidation States of the Elements and Their Potentials in Aqueous Solution," Prentice-Hall, Inc., New York, 1938. Cf. Perry, *op. cit.*

[2] *U.S. Bur. Mines Bull.* 406 (1937).

[3] *U.S. Bur. Mines Bull.* 407 (1937).

[4] *U.S. Bur. Mines Bull.* 384 (1935).

[5] "The Free Energies of Some Organic Compounds," Reinhold Publishing Corporation, New York, 1932.

[6] *Chem. Rev.*, **27**, 39 (1940).

[7] *Ind. Eng. Chem.*, **33**, 584 (1941).

$H_2O = 200 - (100 - y) = 100 + y$	100
$CO = 100 - y$	100
$H_2 = 300 - 3y$	300
$\text{Total} = 500 - 3y$	500

Partial pressure in atmospheres = mole fractions.

$$
\begin{aligned}
CH_4 &= y/500 = 0.002y \\
H_2O &= 100/500 = 0.2 \\
CO &= 100/500 = 0.2 \\
H_2 &= 300/500 = 0.6
\end{aligned}
$$

$$2570 = \frac{(CO)(H_2)^3}{(CH_4)(H_2O)} = \frac{0.2 \times (0.6)^3}{0.002y \times 0.2} = \frac{113}{y}$$

or

$$y = \frac{113}{2{,}570} = 0.04 \text{ moles/100 moles } CH_4 \text{ charged}$$

This is nearly complete conversion justifying the assumption made and the neglect of y in computing the number of moles of H_2O, CO, and H_2.

DISCUSSION: This computation shows that *if* this reaction is rapid and *if* no side reactions are involved, complete conversion of methane may be effected at 1700°F. This reaction is the basis of one commercial process for production of hydrogen. In practice a catalyst (such as nickel) is employed to speed the reaction. Some CO_2 is also formed in accordance with the reaction

$$CO + H_2O = CO_2 + H_2$$

9. Basic Laws and Equations of Physical Thermodynamics

Although laws of thermodynamics are universally applicable, they may be expressed in relatively simple forms when no *changes* in composition are involved. Hence, the distinction between physical and chemical thermodynamics.

a. Law of Conservation of Mass.—This law states that mass is indestructible and may not be destroyed or created by any process.

b. First Law of Thermodynamics. The Law of Conservation of Energy.—This law states that energy is also indestructible, though one form of energy may disappear and reappear as a different form. For example, if a weight is dragged along the ground, the work expended is not lost but is converted to heat.

c. Second Law of Thermodynamics.—There are many ways of stating this law, all of which appear unrelated except that they are uniformly confusing to the novice, and nothing can be done about it. One such statement is that heat cannot be transferred from one temperature to a higher temperature without the expenditure of work. Equation (E-32) is a mathematical statement of this law. The various statements of the law are related to each other as the hen to the egg; the others all follow from the one chosen (arbitrarily) as first.

d. Thermodynamic Functions.

Quantity	Symbol	Definition
Energy content (internal energy)	U	By properties of system
Heat content (enthalpy)	H	$H = U + pV$
Entropy	S	By properties of system
Helmholz free energy	A	$A = U - TS$
Free energy (chemical potential)	F	$F = U + pV - TS$
Absolute temperature	T	Thermodynamic scale
Pressure (absolute)	p	External force/area
Volume	V	By dimensions of system
Specific heat at constant volume	C_v	$C_v = \left(\frac{\partial U}{\partial T}\right)_v = \left(\frac{\partial Q}{\partial T}\right)_v$
Specific heat at constant pressure	C_p	$C_p = \left(\frac{\partial H}{\partial T}\right)_p = \left(\frac{\partial Q}{\partial T}\right)_p$
Heat absorbed by system	Q	Experiment
Work done by system	w	Experiment

The absolute values of the quantities U, H, A, and F are not specified but must be arbitrarily assigned a given value at some standard state of the system. For example, the value of heat contents and entropies given in steam tables are based on $H = S = 0$ for liquid water at 32°F and 1 atm pressure. Entropy does have an absolute value, but this is of no consequence for physical thermodynamics, though it is of value in chemical thermodynamics and statistical mechanics. It may be noted that pure thermodynamics defines the quantities only *mathematically*. If some of the quantities are found experimentally, the thermodynamic equations establish others.

e. Basic Equations, Static Systems.—The following equations are rigorously applicable to any stationary system whether homogeneous or heterogeneous.

Change in energy content at constant volume:

$$\left(\frac{\partial U}{\partial T}\right)_v = C_v = \left(\frac{\partial Q}{\partial T}\right)_v \tag{E-19}$$

or

$$U = U_o + \int C_v\,dT \tag{E-20}$$

Change in heat content at constant pressure:

$$\left(\frac{\partial H}{\partial T}\right)_p = C_p = \left(\frac{\partial Q}{\partial T}\right)_p \tag{E-21}$$

or

$$H = H_0 + \int C_p\,dT \qquad \text{(E-22)}$$

if

$$C_p = a + bT - cT^2 - \frac{d}{T^2} \qquad \text{(E-23)}$$

$$H = H_0 + aT + \tfrac{1}{2}bT^2 - \tfrac{1}{3}cT^3 + \frac{d}{T} \qquad \text{(E-24)}$$

Change in heat content at constant temperature:

$$\left(\frac{\partial H}{\partial p}\right)_T = -\mu C_p \qquad \text{(E-25)}$$

where $\mu = \left(\frac{\partial T}{\partial p}\right)_H$, the Joule-Thomson coefficient determined by measuring the temperature change accompanying a free expansion under adiabatic (perfectly insulated) conditions

Change in entropy at constant pressure:

$$\left(\frac{\partial S}{\partial T}\right)_p = \frac{c_p}{T} \qquad \text{(E-26)}$$

$$S = S_o + \int \frac{C_p}{T}\,dT \qquad \text{(E-27)}$$

Change of entropy at constant temperature:

$$\left(\frac{\partial S}{\partial V}\right)_T = \left(\frac{\partial p}{\partial T}\right)_v \qquad \text{(E-28)}$$

$$\left(\frac{\partial S}{\partial p}\right)_T = -\left(\frac{\partial V}{\partial T}\right)_p \qquad \text{(E-29)}$$

Thermodynamic equation of state:

$$p = T\left(\frac{\partial p}{\partial T}\right)_v - \left(\frac{\partial U}{\partial V}\right)_T \qquad \text{(E-30)}$$

$$V = T\left(\frac{\partial V}{\partial T}\right)_p + \left(\frac{\partial H}{\partial p}\right)_T \qquad \text{(E-31)}$$

Condition for maximum mechanical efficiency of any cyclical process:

$$\oint \frac{dQ}{T} = 0 \qquad \text{(E-32)}$$

This is a statement of the second law. (The symbol $\oint$ denotes integration for one complete cycle which returns system to its original state.)

Condition for maximum efficiency of any process:

$$\frac{dQ}{T} = dS \tag{E-33}$$

(Such a process is said to be a "reversible" one.)

Work produced by any reversible process:

$$w = \int p\,dV = -\Delta U + Q \tag{E-34}$$
$$Q = \int T\,dS \tag{E-35}$$

Work produced by a reversible process at constant temperature:

$$w = \int p\,dv = -\Delta A = -\Delta U + Q \tag{E-36}$$
$$Q = T\,\Delta S \tag{E-37}$$

Work produced by a reversible process at adiabatic conditions (no heat loss or gain):

$$w = \int p\,dv = \Delta H \tag{E-38}$$
$$Q = 0, \qquad \Delta S = 0 \tag{E-39}$$

Relation of work produced to heat absorbed for any process:

$$Q - w = \Delta U \tag{E-40}$$

Equilibrium pressure for phase change:

$$\frac{dp}{dT} = \frac{\Delta H}{T\,\Delta V} \text{ (Clapeyron equation)} \tag{E-17a}$$

f. Basic Equations, Flowing Systems.

Kinetic energy of flow:

$$\text{K.E.} = \frac{mu^2}{2g} \tag{E-41}$$

where u = linear velocity (or root of mean square velocity if system is flowing at a nonuniform velocity)

m = weight of system

g = gravitational acceleration

Potential energy:

$$\text{P.E.} = mZ$$

where Z = height above datum plane

Bernoulli's equation:

$$H_1 + mZ_1 + \frac{mu_1^2}{2g} + Q - w = H_2 + mZ_2 + \frac{mu_2^2}{2g} \tag{E-42}$$

This equation applies to any flowing system when steady flow is established. The subscript (1) refers to material entering system; the subscript (2) refers to material leaving. Q is the heat added to the flowing material between the entrance and exit points; w is the external work done by flowing material between the entrance and exit points.

10. Basic Laws and Equations of Chemical Thermodynamics

Because of the need of speed even at the expense of *last-place* accuracy, many process calculations are made without the benefit of the precise but time-consuming methods of chemical thermodynamics, except by employing thermochemical tabulations supplied by the research worker. However, such refined calculations are desirable when they can be made. Here are included a few of the basic equations for reference.

a. Laws of Chemical Thermodynamics.—The basic laws are identical with physical thermodynamics. An added principle is the third law of thermodynamics which states that the absolute entropy of a perfect crystal is zero when reduced to a temperature of absolute zero. Most substances do form substantially perfect crystals at absolute zero, but many such as carbon monoxide, ice, and spinel minerals form imperfect crystals and do not obey the "law."

Thermodynamic equations may readily be modified to include composition as a variable and thereby treat problems involving composition change (*i.e.*, chemical thermodynamics).

b. Partial Molal Quantities.—These are defined by the following equations:

$$\bar{G}_1 = \frac{\partial G}{\partial n_1}, \qquad \bar{G}_2 = \frac{\partial G}{\partial n_2}, \text{ etc.} \tag{E-43}$$

$$G = n_1\bar{G}_1 + n_2\bar{G}_2 + n_3\bar{G}_3 + \cdots \tag{E-44}$$

where subscripts designate components 1, 2, 3, etc.

G = any extensive property[1] such as V, H, U, A, F, C_p, C_v

n_1 = number of moles, component 1, etc.

Partial molal heat contents, free-energy volumes, heat capacities, etc., may be used directly in the equations of physical thermodynamics, provided that all components are treated in computing over-all effects.

c. Fugacity and Activity.—The equations just given are precise but not always convenient because of the difficulty of experimentally determining the partial molal volumes, heats, etc. The use of partial pressures is much more convenient than the use of partial volumes.

---

[1] An extensive property is proportional to quantity of material. T, p, $\bar{V}_1$, $\bar{H}$, etc., are independent of quantity and are called "intensive" properties.

Consequently the fugacity, an idealized partial pressure, has been devised. The partial pressure of a gas or vapor is defined by:

$$p_1 = N_1 p, \qquad p_2 = N_2 p, \text{ etc.} \tag{E-45}$$

where p_1 = partial pressure, component 1
N_1 = mole fraction of component 1 in the gaseous phase

When the perfect gas law is obeyed, as it is at low pressures,

$$f_1 = p_1 \tag{E-46}$$

where f_1 = fugacity of component 1.

For other conditions (including the solid and liquid phases) the fugacity is defined by the following relation:

$$\bar{F}_1 = RT \ln f_1 + B_1 \tag{E-47}$$

where R = gas-law constant
B_1 = arbitrary constant whose value is so chosen that Eq. (E-46) holds when the conditions for validity are fulfilled

For liquid and solid solutions, it may be more convenient to use the activity, which is an idealized mole fraction and is defined in the same way as the fugacity, except that the additive constant is different:

$$\bar{F}_1 = RT \ln a_1 + F_1^0 \tag{E-48}$$

where a_1 = activity, component 1
F_1^0 = free energy per mole of component in its pure liquid state at same temperature (or solid state, if a solid solution)

For aqueous solutions of inorganic solids the activity is defined as the idealized molality.

For convenience, activity and fugacity data are usually given as activity coefficients, which are defined below:

$$\gamma_1 = \frac{f_1}{p_1} \quad \text{(gases)} \tag{E-49}$$

$$\gamma_1 = \frac{a_1}{N_1} \quad \text{(solutions)} \tag{E-50}$$

$$\gamma_1 = \frac{a_1}{m_1} \quad \text{(aqueous solutions)} \tag{E-51}$$

where γ_1 = activity coefficient of component 1

The basic law of ideal solution is Raoult's law:

$$p_1 = p_1^0 N_1 \tag{E-52}$$

where p_1^0 = vapor pressure, pure liquid component 1
N_1 = mole fraction, component 1

This law is more precisely stated,

$$f_1 = f_1^0 N_1$$

where f_1^0 = fugacity of pure liquid, component 1
f_1 = fugacity of component 1 in mixture

d. Thermodynamics of Chemical Reactions.—A thermodynamic equation of a reaction states the thermodynamic state of the substance in parenthesis after the formula as follows:

(g) gaseous state; standard state at fugacity of 1 atm, unless otherwise stated
(l) liquid or liquid solution; standard state is pure liquid at 1 atm, unless otherwise stated
(aq) aqueous solution; standard state at activity = 1 molal
(s) solid; standard state is pure solid unless otherwise stated
(α), (β), etc., denote different crystalline forms of solids

Below are given three such equations and the corresponding equilibrium constants.

Equation	Equilibrium constant	
	Exact	Approximate
A. $H_2O(l) + C_2H_4(g) = C_2H_5OH(l)$	$K_A = \dfrac{a_{C_2H_5OH}}{a_{H_2O} f_{C_2H_4}}$	$K_A = \dfrac{N_{C_2H_5OH}}{N_{H_2O} p_{C_2H_4}}$
B.* $2Cu^{++}(aq) + 5I^-(aq) = 2CuI(s) + I_3^-(aq)$	$K_B = \dfrac{a_{I_3^-}}{a^2_{Cu^{++}} a^5_{I^-}}$	$K_B = \dfrac{m_{I_3^-}}{m^2_{Cu^{++}} m^5_{I^-}}$
C. $\frac{1}{2}N_2(g) + \frac{3}{2}H_2(g) = NH_3(g)$	$K_C = \dfrac{f_{NH_3}}{f_{N_2}{}^{1/2} f_{H_2}{}^{3/2}}$	$K_C = \dfrac{p_{NH_3}}{p_{N_2}{}^{1/2} p_{H_2}{}^{3/2}}$

* CuI does not form solid solutions with any component present; therefore $a_{CuI} = 1$ and does not appear.

The thermodynamic reaction equations are regarded as expressing the number of moles of the stated substances, that is, $2H_2O(l)$ signifies 2 moles of water. Since the thermodynamic reaction equations specify both the amount and state of the reactants and products, one may speak of the thermodynamic properties of a reaction much the same as one speaks of the thermodynamic properties of a substance.

For example, the entropy of reaction, ΔS, is the sum of the entropies of the products less the entropies of the reactants. Specifically, the entropy of reaction *B* is

$$\Delta S_B = 2S_{CuI} + S_{I_3^-} - 5S_{I^-} - 2S_{Cu^{++}}$$

Similarly,

ΔC_p = heat capacity of reaction
ΔH = heat content of reaction ($-\Delta H$ = heat of reaction)
ΔF = free energy of reaction
ΔV = volume change of reaction

These Δ quantities obey the same equations for their mutual relations as do H, F, S, V, and C_p for single substances.

Because H and F have no absolute, but only relative values, ΔH and ΔF cannot be computed from the properties of reactants and products until a standard state is established which includes chemical as well as physical factors. Fortunately such a standard may be obtained by arbitrarily taking $H = F = 0$ for the elements at 1 atm in their most stable state. The standard heat of formation, $\Delta H°$, is the heat of formation of the substance in question from the elements. The standard free energy of formation is similarly defined. For example, reaction C is the reaction for formation of ammonia. Hence,

$$\Delta H^\circ_{\mathrm{NH_3}} = \Delta H_c$$
$$\Delta F^\circ_{\mathrm{NH_3}} = \Delta F_c$$

From these standard quantities the change in heat content and free energy accompanying any reaction may be computed. For example, in case of reaction A,

$$\Delta H_A = \Delta H^\circ_{\mathrm{C_2H_5OH}} - \Delta H^\circ_{\mathrm{C_2H_4}} - \Delta H^\circ_{\mathrm{H_2O}}$$
$$\Delta F_A = \Delta F^\circ_{\mathrm{C_2H_5OH}} - \Delta F^\circ_{\mathrm{C_2H_4}} - \Delta F^\circ_{\mathrm{H_2O}}$$

Heat of reaction:

The heat liberated by spontaneous reaction at constant temperature and pressure is the *decrease* in heat content:

$$Q_R = \Delta H = \text{heat absorbed}$$
$$-Q_R = \text{heat of reaction}$$

Variation of heat of reaction with temperature:

$$\frac{d\Delta H}{dT} = \Delta C_p = \Delta a + \Delta bT - \Delta cT^2 - \frac{\Delta d}{T^2} \tag{E-53}$$

$$\Delta H = \Delta H_0 + \int \Delta C_p \, dT \tag{E-54}$$
$$\doteq \Delta H_0 + \Delta aT + \frac{\Delta b}{2} T^2 - \frac{\Delta c}{3} T^2 + \frac{\Delta d}{T}$$

Variation of free energy of reaction with temperature:

$$\frac{d\Delta F}{dT} = -\Delta S \tag{E-55}$$

$$\frac{d(\Delta F/T)}{dT} = \frac{-\Delta H}{T^2} \tag{E-56}$$

$$\frac{\Delta F}{T} = \frac{\Delta H_0}{T} - \Delta a \ln T - \frac{\Delta b}{2} T + \frac{\Delta c}{6} T^2 - \frac{\Delta d}{2T^2} + I \tag{E-57}$$

where I is the constant of integration.

Relation between the free energy and equilibrium constant:

$$-\frac{\Delta F}{T} = R \ln k \tag{E-18}$$

CHAPTER F

PIPING, HYDRAULICS, AND FLOW MEASUREMENTS

Here are presented data for sizing pipes, determining pressure drops, and for flow measurements. A number of excellent texts are available on these subjects. A few are listed below:

Goldstein (editor), "Modern Developments in Fluid Dynamics," Oxford, London, 1938.

Rouse, "Fluid Mechanics for Hydraulic Engineers," McGraw-Hill Book Company, Inc., New York, 1938.

O'Brien and Hickox, "Applied Fluid Mechanics," McGraw-Hill Book Company, Inc., New York, 1937.

Vennard, "Elementary Fluid Mechanics," John Wiley & Sons, Inc., New York, 1940.

Russell, "Textbook on Hydraulics," 4th ed., Henry Holt and Company, Inc., New York, 1934.

"Fluid Meters," Part I, 4th ed., American Society of Mechanical Engineers, New York, 1937.

Crocker, "Piping Handbook," McGraw-Hill Book Company, Inc., New York, 1945.

1. Viscosity Data

Viscosity data are presented as follows:

Liquids	Table F-1 and Fig. F-1
Gases at atmospheric pressure	Table F-2 and Fig. F-2
Steam	Table F-3
Compressed gases	Fig. F-3
Hydrocarbon liquids and vapors	Fig. F-4

Figure F-3 is based on the reduced equation of state. It is in fair agreement with most available data but should not be used when direct measurements are available. The critical pressure and temperature must be known for use of this figure. Values for a few substances are given in Table E-2.

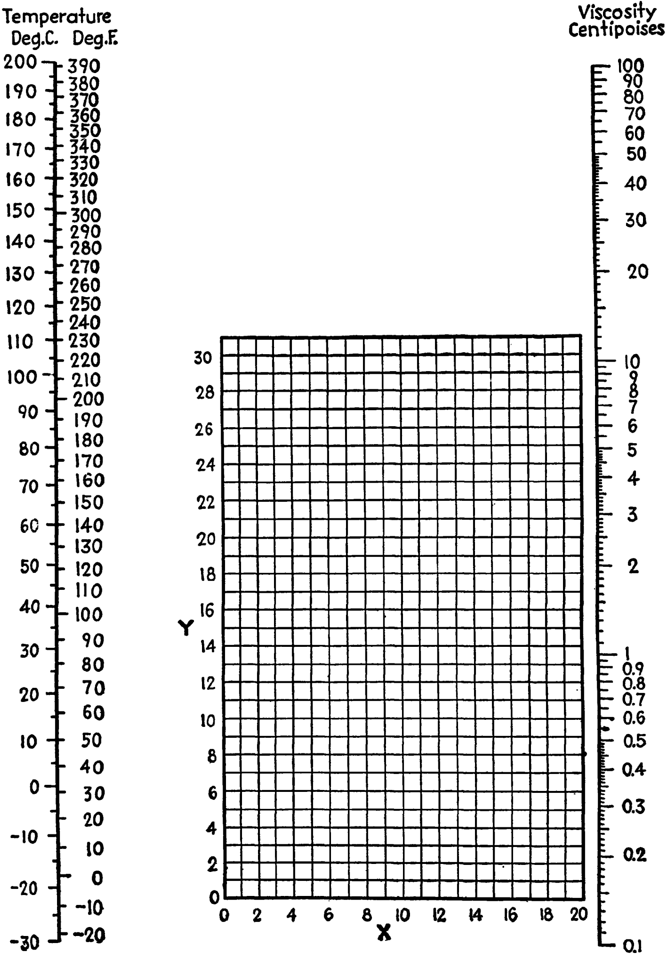


FIG. F-1.—Viscosities of liquids at one atmosphere. For coordinates, see Table F- (*Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, In New York*, 1941.)

TABLE F-1.—VISCOSITIES OF LIQUIDS. COORDINATES FOR FIG. F-1 (Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York, 1941)

No.	Liquid	*X*	*Y*	No.	Liquid	*X*	*Y*
1	Acetaldehyde	15.2	4.8	56	Freon-22	17.2	4.7
2	Acetic acid, 100%	12.1	14.2	57	Freon-113	12.5	11.4
3	Acetic acid, 70%	9.5	17.0	58	Glycerol, 100%	2.0	30.0
4	Acetic anhydride	12.7	12.8	59	Glycerol, 50%	6.9	19.6
5	Acetone, 100%	14.5	7.2	60	Heptene	14.1	8.4
6	Acetone, 35%	7.9	15.0	61	Hexane	14.7	7.0
7	Allyl alcohol	10.2	14.3	62	Hydrochloric acid, 31.5%	13.0	16.6
8	Ammonia, 100%	12.6	2.0	63	Isobutyl alcohol	7.1	18.0
9	Ammonia, 26%	10.1	13.9	64	Isobutyric acid	12.2	14.4
10	Amyl acetate	11.8	12.5	65	Isopropyl alcohol	8.2	16.0
11	Amyl alcohol	7.5	18.4	66	Kerosene	10.2	16.9
12	Aniline	8.1	18.7	67	Linseed oil, raw	7.5	27.2
13	Anisole	12.3	13.5	68	Mercury	18.4	16.4
14	Arsenic trichloride	13.9	14.5	69	Methanol, 100%	12.4	10.5
15	Benzene	12.5	10.9	70	Methanol, 90%	12.3	11.8
16	Brine, $CaCl_2$, 25%	6.6	15.9	71	Methanol, 40%	7.8	15.5
17	Brine, NaCl, 25%	10.2	16.6	72	Methyl acetate	14.2	8.2
18	Bromine	14.2	13.2	73	Methyl chloride	15.0	3.8
19	Bromotoluene	20.0	15.9	74	Methyl ethyl ketone	13.9	8.6
20	Butyl acetate	12.3	11.0	75	Naphthalene	7.9	18.1
21	Butyl alcohol	8.6	17.2	76	Nitric acid, 95%	12.8	13.8
22	Butyric acid	12.1	15.3	77	Nitric acid, 60%	10.8	17.0
23	Carbon dioxide	11.6	0.3	78	Nitrobenzene	10.6	16.2
24	Carbon disulfide	16.1	7.5	79	Nitrotoluene	11.0	17.0
25	Carbon tetrachloride	12.7	13.1	80	Octane	13.7	10.0
26	Chlorobenzene	12.3	12.4	81	Octyl alcohol	6.6	21.1
27	Chloroform	14.4	10.2	82	Pentachloroethane	10.9	17.3
28	Chlorosulphonic acid	11.2	18.1	83	Pentane	14.9	5.2
29	Chlorotoluene, ortho	13.0	13.3	84	Phenol	6.9	20.8
30	Chlorotoluene, meta	13.3	12.5	85	Phosphorus tribromide	13.8	16.7
31	Chlorotoluene, para	13.3	12.5	86	Phosphorus trichloride	16.2	10.9
32	Cresol, meta	2.5	20.8	87	Propionic acid	12.8	13.8
33	Cyclohexanol	2.9	24.3	88	Propyl alcohol	9.1	16.5
34	Dibromoethane	12.7	15.8	89	Propyl bromide	14.5	9.6
35	Dichloroethane	13.2	12.2	90	Propyl chloride	14.4	7.5
36	Dichloromethane	14.6	8.9	91	Propyl iodide	14.1	11.6
37	Diethyl oxalate	11.0	16.4	92	Sodium	16.4	13.9
38	Dimethyl oxalate	12.3	15.8	93	Sodium hydroxide, 50%	3.2	25.8
39	Diphenyl	12.0	18.3	94	Stannic chloride	13.5	12.8
40	Dipropyl oxalate	10.3	17.7	95	Sulphur dioxide	15.2	7.1
41	Ethyl acetate	13.7	9.1	96	Sulphuric acid, 110%	7.2	27.4
42	Ethyl alcohol, 100%	10.5	13.8	97	Sulphuric acid, 98%	7.0	24.8
43	Ethyl alcohol, 95%	9.8	14.3	98	Sulphuric acid, 60%	10.2	21.3
44	Ethyl alcohol, 40%	6.5	16.6	99	Sulphuryl chloride	15.2	12.4
45	Ethyl benzene	13.2	11.5	100	Tetrachloroethane	11.9	15.7
46	Ethyl bromide	14.5	8.1	101	Tetrachloroethylene	14.2	12.7
47	Ethyl chloride	14.8	6.0	102	Titanium tetrachloride	14.4	12.3
48	Ethyl ether	14.5	5.3	103	Toluene	13.7	10.4
49	Ethyl formate	14.2	8.4	104	Trichloroethylene	14.8	10.5
50	Ethyl iodide	14.7	10.3	105	Turpentine	11.5	14.9
51	Ethylene glycol	6.0	23.6	106	Vinyl acetate	14.0	8.8
52	Formic acid	10.7	15.8	107	Water	10.2	13.0
53	Freon-11	14.4	9.0	108	Xylene, ortho	13.5	12.1
54	Freon-12	16.8	5.6	109	Xylene, meta	13.9	10.6
55	Freon-21	15.7	7.5	110	Xylene, para	13.9	10.9

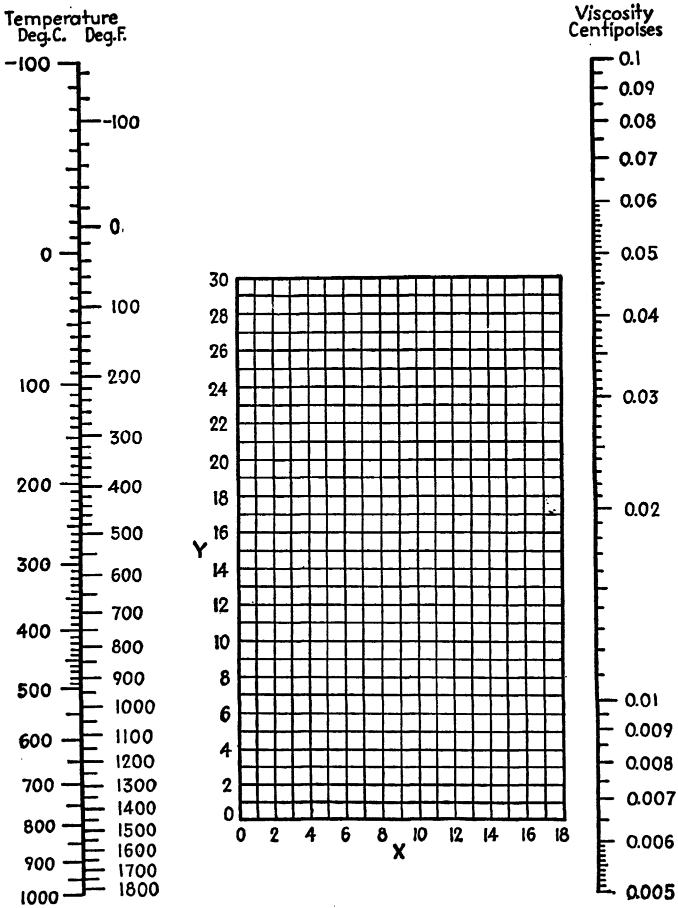


Fig. F-2.—Viscosities of gases at one atmosphere. For coordinates, see Table F-2. (*Perry, "Chemical Engineers' Handbook,"* 2d *ed., McGraw-Hill Book Company, Inc., New York*, 1941.)

Table F-2.—Viscosities of Gases. Coordinates for Fig. F-2
(Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York, 1941)

No.	Gas	*X*	*Y*	No.	Gas	*X*	*Y*
1	Acetic acid	7.7	14.3	29	Freon-113	11.3	14.0
2	Acetone	8.9	13.0	30	Helium	10.9	20.5
3	Acetylene	9.8	14.9	31	Hexane	8.6	11.8
4	Air	11.0	20.0	32	Hydrogen	11.2	12.4
5	Ammonia	8.4	16.0	33	$3H_2 + 1N_2$	11.2	17.2
6	Argon	10.5	22.4	34	Hydrogen bromide	8.8	20.9
7	Benzene	8.5	13.2	35	Hydrogen chloride	8.8	18.7
8	Bromine	8.9	19.2	36	Hydrogen cyanide	9.8	14.9
9	Butene	9.2	13.7	37	Hydrogen iodide	9.0	21.3
10	Butylene	8.9	13.0	38	Hydrogen sulphide	8.6	18.0
11	Carbon dioxide	9.5	18.7	39	Iodine	9.0	18.4
12	Carbon disulfide	8.0	16.0	40	Mercury	5.3	22.9
13	Carbon monoxide	11.0	20.0	41	Methane	9.9	15.5
14	Chlorine	9.0	18.4	42	Methyl alcohol	8.5	15.6
15	Chloroform	8.9	15.7	43	Nitric oxide	10.9	20.5
16	Cyanogen	9.2	15.2	44	Nitrogen	10.6	20.0
17	Cyclohexane	9.2	12.0	45	Nitrosyl chloride	8.0	17.6
18	Ethane	9.1	14.5	46	Nitrous oxide	8.8	19.0
19	Ethyl acetate	8.5	13.2	47	Oxygen	11.0	21.3
20	Ethyl alcohol	9.2	14.2	48	Pentane	7.0	12.8
21	Ethyl chloride	8.5	15.6	49	Propane	9.7	12.9
22	Ethyl ether	8.9	13.0	50	Propyl alcohol	8.4	13.4
23	Ethylene	9.5	15.1	51	Propylene	9.0	13.8
24	Fluorine	7.3	23.8	52	Sulphur dioxide	9.6	17.0
25	Freon-11	10.6	15.1	53	Toluene	8.6	12.4
26	Freon-12	11.1	16.0	54	2,3,3-Trimethylbutane	9.5	10.5
27	Freon-21	10.8	15.3	55	Water	8.0	16.0
28	Freon-22	10.1	17.0	56	Xenon	9.3	23.0

Table F-3.—Viscosity of Steam
[Data of Hawkins, Solberg, and Potter, *Trans. Am. Soc. Mech. Engrs.*, **62,** 677 (1940)]
Values in centipoise

Temp.		Pressure, lb force/sq in. abs					
°C	°F	100	200	400	500	600	800
204	400	0.0198	0.0230				
260	500	0.0213	0.0236	0.0272	0.0289	0.0311	
316	600	0.0228	0.0246	0.0279	0.0294	0.0314	0.0350
371	700	0.0243	0.0259	0.0290	0.0304	0.0321	0.0357
427	800	0.0260	0.0275	0.0304	0.0318	0.0334	0.0370
482	900	0.0278	0.0292	0.0320	0.0335	0.0352	0.0390
538	1000	0.0296	0.0310	0.0338	0.0354	0.0372	0.0414

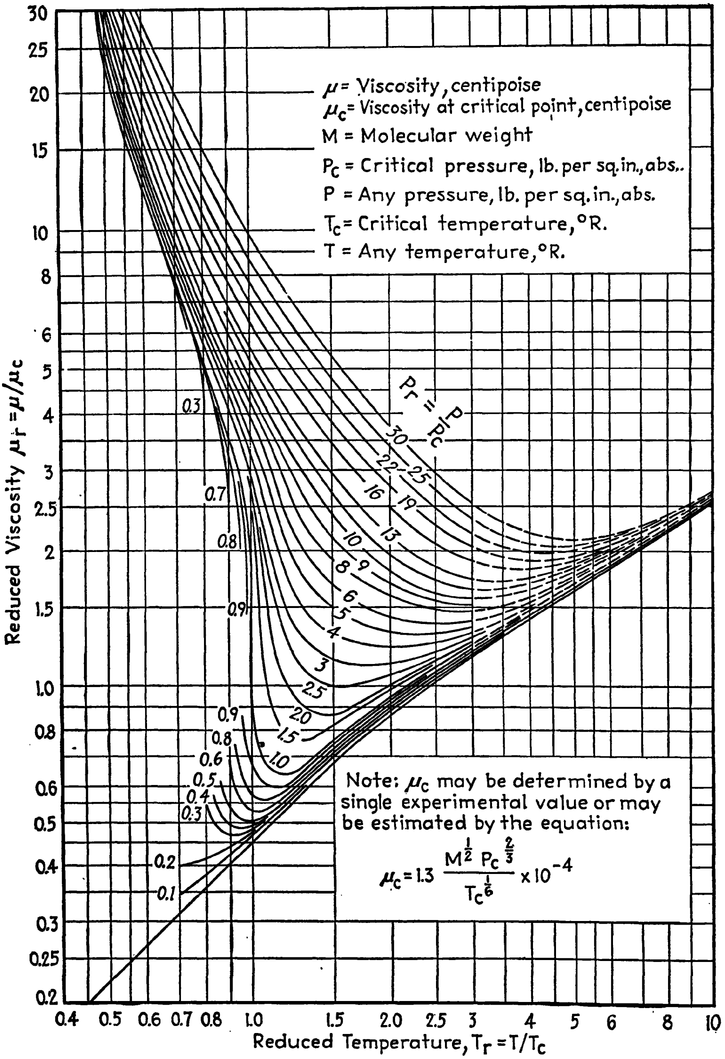


FIG. F-3.—A universal viscosity correlation. (*Uyehara and Watson, National Petroleum News, Technical Section, Oct. 4, 1944.*)

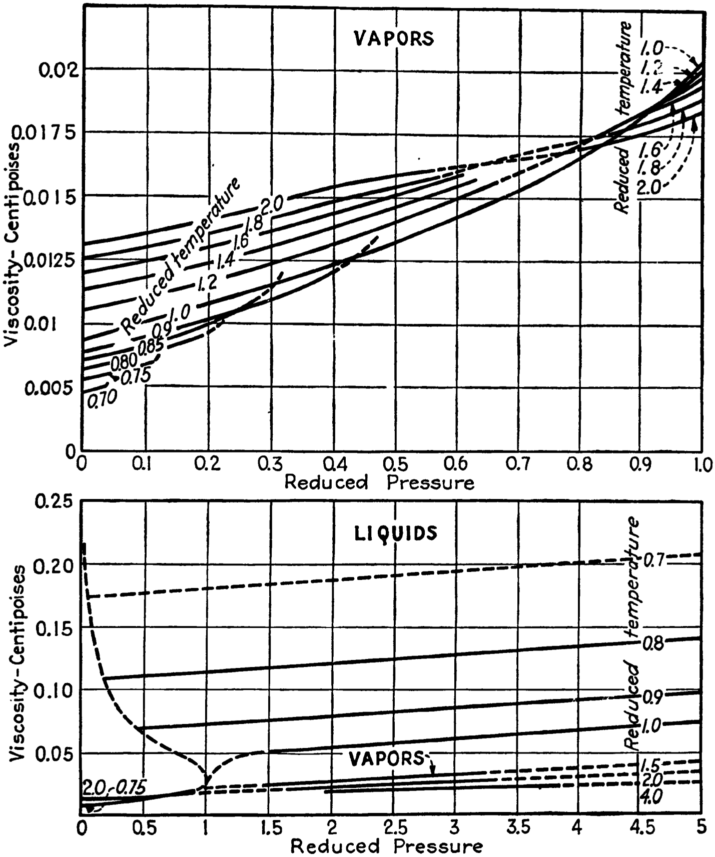


FIG. F-4.—Viscosity of hydrocarbon liquids and vapors. (*Nelson, "Petroleum Refinery Engineering," 2d ed., McGraw-Hill Book Company, Inc., New York,* 1941.)

2. Flow Measurements

a. Basic Equations.—Bernoulli's theorem is a convenient starting point in the study of hydraulics. This theorem results from the application of the first law of thermodynamics to moving fluids, that is, from an energy balance for the liquid entering "the system at point 1" and leaving at "point 2." The theorem is stated below for 1 lb of flowing fluid and units of foot-pounds.

$$JU_2 + p_2V_2 + \frac{u_2^2}{2g} + Z_2 + JQ - w = JU_1 + p_1V_1 + \frac{u_1^2}{2g} + Z_1 \quad \text{(F-1)}$$

where J = 778.1 ft-lb/Btu, the mechanical equivalent of heat
g = 32.17 ft/sec², the gravitational acceleration
p_1, p_2 = initial and final pressures, psf
V_1, V_2 = initial and final volumes, cu ft/lb
Z_1, Z_2 = initial and final heights, in feet above a datum plane, ft
U_1, U_2 = initial and final internal energy, Btu/lb
Q = heat absorbed from surroundings, Btu/lb between points 1 and 2
w = net *external* work done by fluid traveling between points 1 and 2
u_1, u_2 = initial and final average velocities, fps

Equation (F-1) is sufficiently general for treatment of almost any flow problem and may be greatly simplified for particular problems. We shall consider the case of horizontal flow of an incompressible fluid through a "perfect" orifice or venturi, that is, one in which friction is entirely negligible. Under these conditions, $U_2 = U_1$, $V_2 = V_1 = V$, $Q = W = 0$, $Z_2 = Z_1$, and Eq. (F-1) reduces to

$$p_1 - p_2 = \frac{u_2^2 - u_1^2}{2gV} \tag{F-2}$$

This equation may be used for computing the flow through orifices and nozzles by including an experimental factor, the coefficient of discharge. The velocities, of course, may be computed from the flows and diameters involved, and this computation may be incorporated into the equation. This has been done in the working equations in the next section.

In the case of gases, correction for their expansion in flow through an orifice is necessary. From thermodynamic considerations it may be shown that the pressure-volume relation of a perfect gas in frictionless flow, when no work is done and no heat is lost or gained, is

$$p_2 V_2^{\gamma} = p_1 V_1^{\gamma}$$

where p_1, p_2 = upstream and downstream pressures
V_1, V_2 = upstream and downstream specific volumes

$$\gamma = \frac{C_p - R}{C_p} = \frac{C_v}{C_p} \text{ (for perfect gases)}$$

C_p = specific heat at constant pressure
C_v = specific heat at constant volume
R = perfect gas constant, 1.968 Btu/(lb mole)(°F)

This may be introduced in Eq. (F-1), and the result leads to the theoretical value of the expansion factor given by Eq. (F-3). The addition of this factor to flow equations for incompressible fluids makes the result applicable to gases.

$$Y_2 = \sqrt{\frac{r}{n}\left(\frac{1-r^n}{1-r}\right)\left(\frac{1-\beta^4}{r^{2n}-\beta^4 r^2}\right)} \qquad \text{(F-3)}$$

where Y_2 = expansion factor based on *downstream* pressure

$r = \frac{p_2}{p_1}$

p_1, p_2 = upstream and downstream pressures

$n = \frac{C_p - C_v}{C_p} = \frac{R}{C_p} = \frac{\gamma - 1}{\gamma}$ (for perfect gases)

C_p, C_v = specific heats at constant pressure, volume

$\gamma = \frac{C_p}{C_v}$

R = gas constant

β = ratio of orifice to pipe diameter

It will be noted that the expansion factor Y_2, as given, is based on the downstream pressure. As this results in values near unity, the factor may be neglected entirely for most cases. Numerical values of Y_2 are given in Fig. F-5. The values given for nozzles and venturis are computed from Eq. (F-3). For sharp-edge orifices experimental values are given.[1] Some workers prefer to use the *upstream* pressure as the basis for orifice calculations. If this is done, the expansion factors are different.

b. Working Equations for Flow Calculations.

Weight discharge for any fluid:

$$\begin{aligned} W &= \frac{358.9CY_2d^2}{\sqrt{1-\beta^4}}\sqrt{\rho h_w} = 358.9KY_2d^2\sqrt{\rho h_w} \\ &= \frac{358.9CY_2d^2}{\sqrt{1-\beta^4}}\sqrt{\frac{h_w}{V}} = 358.9KY_2d^2\sqrt{\frac{h_w}{V}} \qquad \text{(F-4)} \end{aligned}$$

Volume discharge of a liquid:

$$\begin{aligned} m &= \frac{44.75Cd^2}{\sqrt{1-\beta^4}}\sqrt{\frac{h_w}{\rho}} = 44.75Kd^2\sqrt{\frac{h_w}{\rho}} \\ &= \frac{5.667Cd^2}{\sqrt{1-\beta^4}}\sqrt{\frac{h_w}{s}} = 5.667Kd^2\sqrt{\frac{h_w}{s}} \qquad \text{(F-5)} \end{aligned}$$

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[1] "Fluid Meters," Part I, 4th ed., American Society of Mechanical Engineers, New York, 1937.

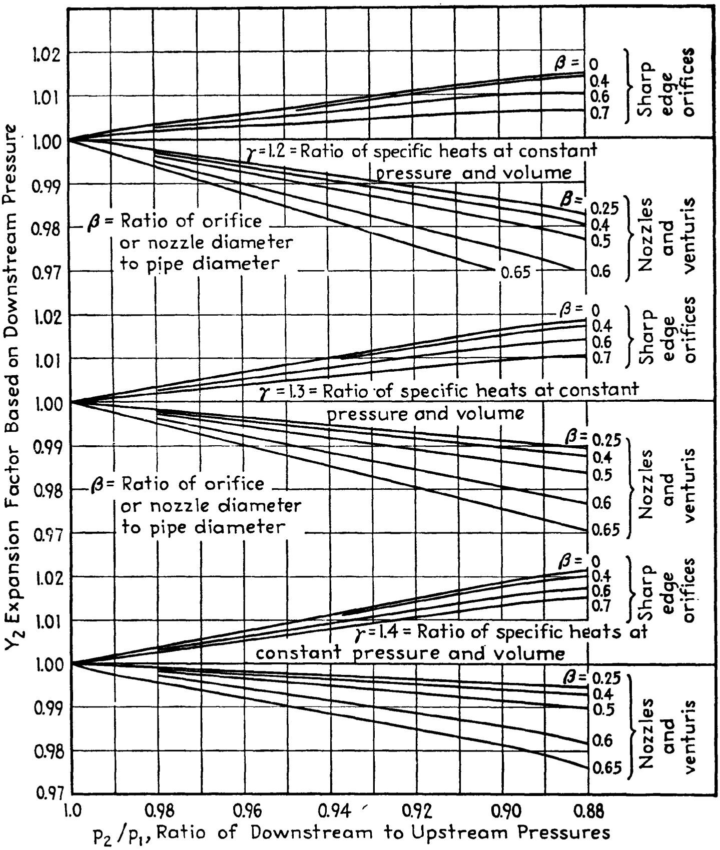

FIG. F-5.—Expansion factors for gas flow through orifices, nozzles, and venturis.

Volume flow of gases:

$$M = \frac{128.5CY_2d^2}{\sqrt{1 - \beta^4}} \sqrt{\frac{p_2h_w}{zTS}} = 128.5KY_2d^2 \sqrt{\frac{p_2h_w}{zTS}} \qquad \text{(F-6)}$$

where W = flow rate, lb/hr
m = flow rate, gpm
M = flow rate, SCF/min (1 SCF = cu ft of gas at 60°F and 30 in. Hg.)
C = coefficient of discharge (see Figs. F-6, F-8, and F-11)
= ratio of actual discharge to discharge of perfect orifice

$K = \dfrac{C}{\sqrt{1 - \beta^4}}$ = coefficient of discharge including velocity of approach (see Figs. F-7, F-9, and F-10)
h_w = differential head, in. water (60°F)
$\beta = \dfrac{d}{D}$
d = internal diameter of orifice, nozzle, or venturi, in.
D = internal diameter of upstream pipe, in.
ρ = fluid density, lb/cu ft (for gases, measured at T and p_2)
T = absolute temperature, °R (upstream conditions)
p_2 = absolute pressure, psi, at downstream tap
s = specific gravity, referred to water at 60°F
S = specific gravity of gas relative to air, $\dfrac{\text{molecular weight}}{28.9}$
V = specific volume, cu ft/lb, (for gases, measured at T and p_2)
z = compressibility factor for gas, the ratio of actual to perfect gas law volumes (see Figs. E-1 to E-3)
Y_2 = expansion factor for gases based on downstream pressure (see Fig. F-5)

These equations all give the differential head in terms of inches of water. For other manometer fluids, multiply the head by the specific gravity of the manometer liquid. Many meters use mercury as the manometer fluid but are calibrated in inches of water, or in square root of inches of water. Such readings may be used directly when metering gases without the use of a seal fluid. When a liquid is measured, a correction must be made for the density of fluid. This may be done by multiplying the recorded head by the factor

$$\frac{13.6 - s}{13.6}$$

where s is the specific gravity of the liquid and 13.6 is the specific gravity of mercury. In the case of gases that attack mercury a seal liquid is usually employed. The same factor may be used if the seal pots are large in diameter compared to the diameter of the mercury pots; otherwise a more complicated correction taking care of the change in level of the seal liquid in the seal pots must be made.

Coefficients of discharge for use in these equations are given as follows:

Venturi meters	Fig. F-6
I. S. A. nozzles	Fig. F-7
A. S. M. E. nozzles	Fig. F-8
Sharp-edge orifices	Figs. F-9 to F-11

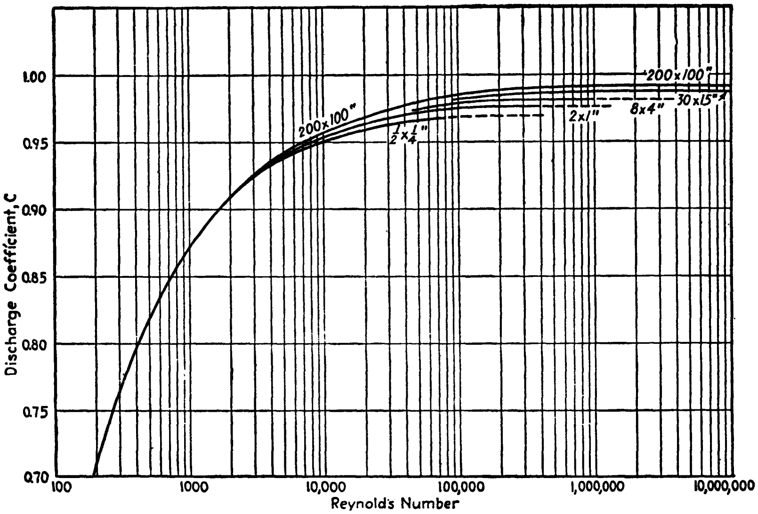

FIG. F-6.—Discharge coefficients for Herschel's design venturi tubes. New tubes with cast-iron body and bronze throat having a diameter ratio of 0.50. (*Data from Fluid Meters, Part I. 4th ed., Am. Soc. Mech. Eng., New York,* 1937.)

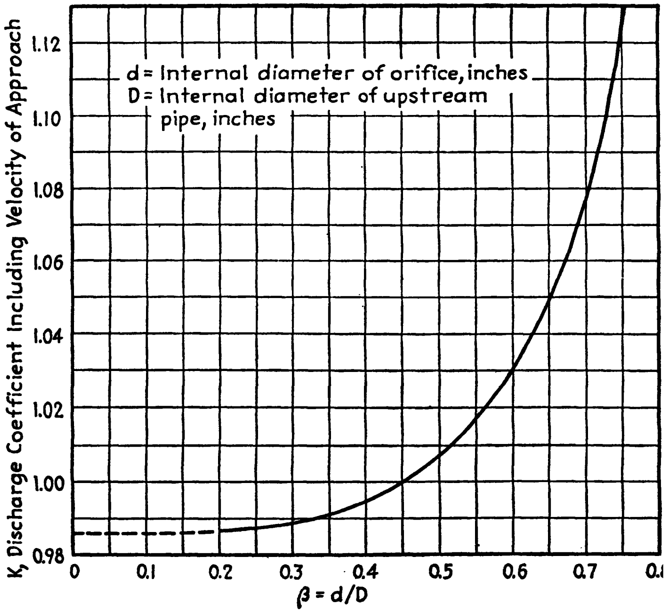

FIG. F-7.—Discharge coefficients for I. S. A. (German Standard) rounded entrance nozzles. (*Adapted by permission from "Elementary Fluid Mechanics," by J. K. Vennard, published by John Wiley & Sons, Inc., New York,* 1940.)

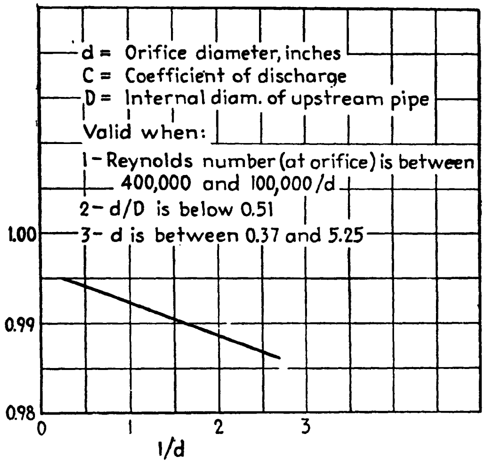

FIG. F-8.—Tentative values of discharge coefficients of A.S.M.E. long-radius nozzles. (*Fluid Meters, Part I, 4th ed., Am. Soc. Mech. Eng., New York,* 1937.)

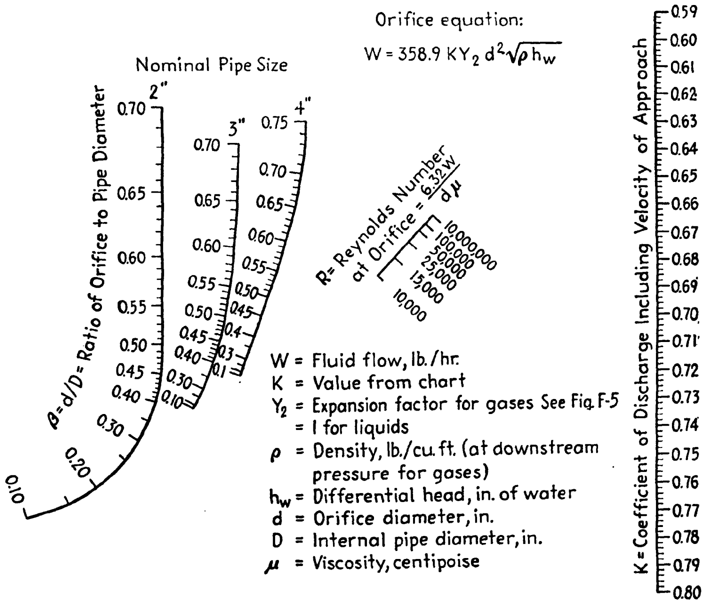

FIG. F-9.—Discharge coefficients including velocity of approach for sharp-edge orifices with flange taps. (*Based on data from Fluid Meters, Part I, 4th ed., Am. Soc. Mech. Eng., New York,* 1937.)

From these figures it will be noted that coefficients of discharge depend on the ratio of orifice to pipe diameter and on the Reynolds number. This number [defined by Eq. (F-10)] is basic to the friction

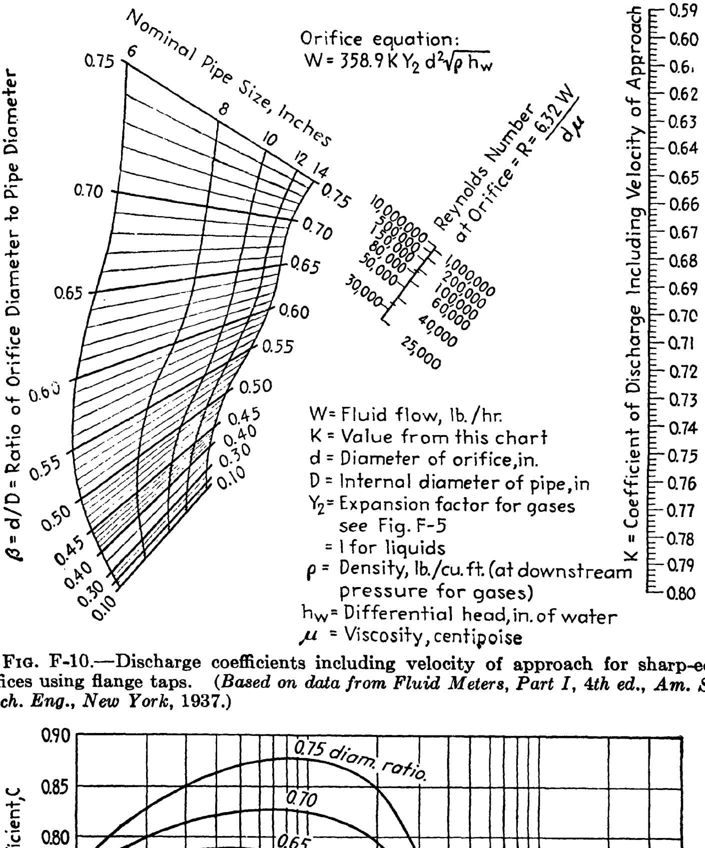

FIG. F-10.—Discharge coefficients including velocity of approach for sharp-edge orifices using flange taps. (*Based on data from Fluid Meters, Part I, 4th ed., Am. Soc. Mech. Eng., New York,* 1937.)

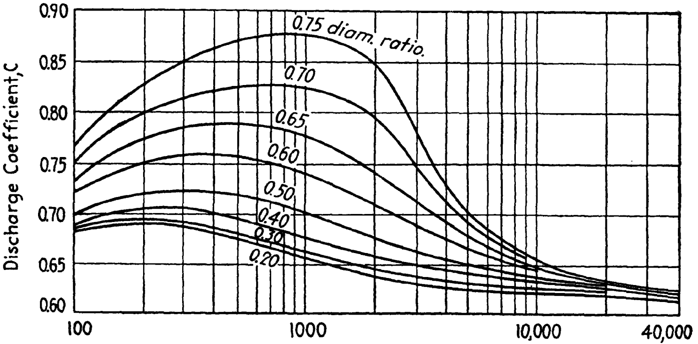

FIG. F-11.—Coefficients of sharp-edge orifices. Applicable to flange or vena contracta taps. [*Tuve and Sprenkle, Instruments* **6**, 201 (1933).]

accompanying flow and will be discussed in the next section. In the case of sharp-edge orifices two sets of data are given. Figures F-9 and F-10 cover the usual range; Fig. F-11 covers the range of low Reynolds numbers which are encountered in metering viscous liquids.

In theory, it would be desirable to correct every single measurement for the Reynolds number at that flow. Practically, such refinement is not desirable, as a constant factor corresponding to average values of Reynolds number may be employed for the relatively narrow range of a flow meter without real loss of accuracy. To illustrate the use of these working equations Example F-1 is presented.

Example F-1. Size an orifice and compute the meter coefficient for flow of 1,000 SCF/min of carbon dioxide in an 8-in. pipe at a temperature of 90°F and a pressure of 10 psig. Assume that a 50-in. meter is to be used and that the meter gives satisfactory accuracy down to a head of 10 in. of water.

SOLUTION:

1. Size of orifice,

$$M = 128.5KY_2d^2\sqrt{\frac{p_2h_w}{zTS}} \qquad \text{Eq. (F-6)}$$

where $M = 1{,}000$ SCF/min
$KY_2 = 0.62$ (trial assumption)
$T = 90 + 460 = 550°\text{R}$
$S = \dfrac{44}{28.9} = 1.519$
(44 = molecular weight of CO_2)
$h_w = 25$ in. of water (½ of head at full scale)
$p_2 = 10 + 14.7 - \frac{25}{12} \times 0.434 = 24.7 - 0.9 = 23.8$ psi
$z = 0.97$ (from Fig. E-1)

$$1{,}000 = 128.5 \times 0.62d^2\sqrt{\frac{23.8 \times 25}{0.97 \times 550 \times 1.519}} = 79.7d^2\sqrt{0.734}$$

$$d^2 = \frac{1{,}000}{68.2} = 14.66$$

$d = 3.83$ in., say 3⅞ as a tentative value
(subject to change if assumed value of KY_2 is in error)

2. Meter coefficient,

Approximate mass flow,

$$W = \frac{1{,}000 \times 44}{379} = 116 \text{ lb/min or } 7{,}000 \text{ lb/hr (round value)}$$

(1 mole = 378.7 SCF)
Viscosity = 0.015 centipoise, from Fig. F-2

Reynolds number,

$$R = \frac{6.32W}{d\mu} = \frac{6.32 \times 7{,}000}{0.015 \times 3.875} = 760{,}000 \qquad \text{[Eq. (F-10)]}$$

Orifice coefficient,

$$\beta = \frac{d}{D} = \frac{3.875}{8.07} = 0.48$$
$$K = 0.620, \text{ from Fig. F-10}$$

Expansion ratio,

$$\frac{p_2}{p_1} = \frac{23.8}{24.7} = 0.964$$

Specific heat,

$$C_p = 9.0 \text{ Btu/(lb mole)(°F)} \qquad \text{(Fig. E-5)}$$
$$\gamma = \frac{C_p}{C_p - R} = \frac{9.0}{9.0 - 1.986} = \frac{9.0}{7.01} = 1.29$$

Expansion factor,

$$\gamma = 1.3, \qquad Y_2 = 1.006 \qquad \text{(Fig. F-5)}$$

Flow equation,

$$\begin{aligned} M &= 128.5KY_2d^2\sqrt{\frac{p_2h_w}{zTS}} \\ &= 128.5 \times 0.620 \times 1.006 \times (3.875)^2\sqrt{\frac{p_2h_w}{0.97 \times 1.519T}} \\ &= 989\sqrt{\frac{p_2h_w}{T}} \end{aligned}$$

(This equation may be used for all further calculations for this installation as the factors KY_2 and z do not vary much within the range of the meter.)

3. Check on orifice size,

Maximum meter reading, $h_w = 50$

$$\begin{aligned} M &= 989\sqrt{\frac{23.6 \times 50}{550}} \\ &= 1{,}450 \text{ SCF/min} \end{aligned}$$

Minimum meter reading for good accuracy, $h_w = 10$

$$M = 648 \text{ SCF/min}$$

This justifies the choice of orifice size as the normal reading is well within the useful range.

DISCUSSION: This example is considerably more detailed than is frequently necessary. Some instrument companies recommend coefficients dependent only on the diameter ratio, β, and whether the fluid metered is a liquid or a gas. Since fluids are bought and sold on the basis of these factors, it may be appreciated that only a moderate error is introduced.

c. Accuracy of Measurements.—The coefficients given for venturis and nozzles are based on data accurate to 1 per cent. The accuracy of the coefficients for sharp-edge orifices, as read in Figs. F-9 and F-10, are better than 1 per cent for all but a small portion of the range. The maximum error is probably no more than 1.3 per cent for extreme values of Reynolds numbers. The coefficients presented in Fig. F-11 are stated to be accurate to 1.5 per cent. For more detailed information on accuracy, the reader is referred to the references accompanying the figures. It should be noted that these accuracies make no allowance for added error introduced by the measuring instrument. The accuracies quoted by instrument companies usually refer to full-scale reading where error is at a minimum. Taking account of inevitable minor imperfections of commercial installations and inaccuracy of the metering instrument, over-all accuracies may be expected to be in the range of 2 to 3 per cent. In any event, careful installations are essential, and the directions of instrument companies or standard texts should be followed closely to avoid large errors.

d. Other Methods of Flow Measurement.—Formerly a scientific curiosity, the rotometer has become a popular method of flow measurement. It presents the advantage of visibility so that fouling is at once detected and corrected before causing large error. Further, rotometers permit accurate measurement over a wide range; and scales of infinite variety may be obtained for special uses. They are particularly advantageous for liquids, since a proper choice of float makes meter reading directly proportional to the weight flow without correction for density or viscosity. The large variety of rotometers prevents giving coefficients here, but such information is readily available from the manufacturer. The theory of rotometer is presented by Schoenborn and Colburn[1] and, to some extent, in standard texts.

The flow of liquids from an open channel over, or through, a wide variety of dams, notches, or other openings has been studied. Here will be given equations for sharp-edge rectangular and triangular weirs where the velocity of liquid approaching the weir is low. For rectangular weirs with vertical sides and one edge horizontal the Francis formula is usually employed:

$$m = 3.0(L + 0.2h)h^{3/2} \qquad \text{(F-7)}$$

where m = flow, gpm
L = length of crest, in.
h = head of liquid, in.
= difference in level of body of liquid and bottom of weir

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[1] *Trans. Am. Inst. Chem. Engrs.*, **35**, 359 (1939).

According to Perry[1] this equation is accurate 3 per cent or less when

1. L is greater than $2h$,
2. Height of crest above the bottom of upstream channel is at least $3h$,
3. Velocity of approach is 1 fps or less,
4. h is not less than 3.6 in.

For triangular V-notch weirs cut with the vertex downward Greve[2] gives

$$w = 610 \left(\frac{L}{H}\right)^{0.996} h^{2.47} \tag{F-8}$$

where w = flow, lb/hr
L = breadth of notch at top, in.
H = height of notch, in.
h = head of liquid, in.

This equation is accurate for water. For other liquids Perry[3] suggests multiplying the flow [computed by Eq. (F-8)] by the factor

$$\left(\frac{\mu}{s}\right)^{0.02}$$

where μ = viscosity, centipoise
s = specific gravity referred to water at 60°F

When large pressure drops are available, the phenomenon of "unrestricted flow" is useful for measuring the flow of gases. If the pressure drop through a nozzle is great enough so that the ratio of downstream to upstream pressures (absolute units) is below a critical value (about one-half for most gases), then the flow becomes proportional to the upstream pressure only, entirely independent of the downstream pressure. Thus a pressure gauge and a nozzle may serve as a flow meter. Coefficients of discharge in this type of service are slightly higher than for the usual "restricted" flow. Very much the same phenomenon occurs for sharp-edge orifices, but the coefficients of discharge are not well known.

Positive-displacement meters are in wide use for metering fluids but require no particular discussion since they are customarily calibrated to read the volume flow directly. The volume measured is, of course, that under the conditions prevailing at the meter; if the volume of the fluid is desired at other temperatures and pressures, a correction must be made.

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[1] Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York, 1941.

[2] *Eng. News-Record,* **105,** 166 (1930).

[3] Perry, *op. cit.*

3. Pressure Drops in Pipes

a. General Notes.—Piping usually represents a very important fraction of the cost of constructing a chemical plant. Consequently the proper selection of pipe sizes is important. Usually it is necessary to make a preliminary guess as to the proper size and estimate the resulting pressure drop, before adopting the final size of the line in question. Figure F-15 and Table F-5, given under special methods, will be found useful for making preliminary guesses. This section presents, first, the general method of estimating pressure drops, followed by special methods which are less time-consuming.

The problem of estimating pressure drops is complicated by the existence of two types of fluid flow: laminar (also called "streamline" or "viscous") and turbulent. Laminar flow is characteristic of low velocities, and its nature may be likened to the orderly march of soldiers. Turbulent flow resembles herding of sheep and occurs at higher velocities. Most commercial piping is designed for high velocities in the turbulent range unless viscous materials are being handled.

b. Laminar Flow and the Reynolds Number.—The pressure drop through straight pipe arises almost entirely from friction since velocity is constant. Since the pipe walls are dense compared to fluids, it would be expected that friction between the walls and the liquid in immediate contact would be somewhat larger than between two layers of liquid. This is usually the case and, consequently, even though the fluid may be moving at high velocity in the center of the tube, the liquid very near the walls will be nearly stationary. If one carries this to the extreme, the molecules in direct contact with the walls may best be regarded as at rest. The measure of friction between liquid layers is the viscosity. One unit of viscosity, the poise, is defined as the force in dynes required to maintain a centimeter per second velocity difference between adjacent liquid "films" of 1 sq cm area. This definition is highly theoretical and does not at once present a clear picture of the property. Nevertheless, using this "definition" and the idea that the molecules in contact with the pipe are stationary, one may set up a differential equation for laminar flow. This may be integrated to obtain Eq. (F-9). This is called the "Poiseuille equation" and is the basis for the Ostwald type of viscometer. Equation (F-9) may, therefore, be regarded as a *practical* definition of viscosity. Conversely, given the viscosity of a fluid, the equation may be used to predict the pressure drops for laminar flow.

$$\Delta p = \frac{0.000034 L \mu W}{\rho d^4} = \frac{0.000273 L \mu q}{d^4} \qquad \text{(F-9)}$$

where Δp = pressure drop, psi
L = length of pipe, ft
q = flow, gpm
W = flow, lb/hr
ρ = fluid density, lb/cu ft
d = inside diameter of pipe, in.
μ = fluid viscosity, centipoise

The transition from laminar to turbulent flow is complex. Nevertheless, the more important factors are adequately covered by the Reynolds number. This number is a dimensionless quantity; that is, its value is the same when calculated from any *consistent* set of units whether based on pounds, seconds, and feet, or on grams, seconds, and centimeters. Equation (F-10) defines Reynolds number in terms of a variety of convenient though *inconsistent* units.

$$R = \frac{D_e u \rho}{\mu_e} = \frac{124 d_e u \rho}{\mu} = \frac{50.7 m \rho}{d \mu} = \frac{6.32 W}{d \mu} \qquad \text{(F-10)}$$

where R = Reynolds number
D_e = equivalent diameter, ft = inside diameter if circular
$= 4 \times \frac{\text{area}}{\text{perimeter}}$ (see Table F-4)
d_e = equivalent diameter, in.
d = diameter of circular pipe, in.
u = average velocity, fps
μ_e = viscosity, lb/(ft)(sec)
μ = viscosity, centipoise
m = flow, gpm
W = flow, lb/hr
ρ = density, lb/cu ft

As a rule, flow will be laminar when R is below 1,200, and turbulent when above 2,300. Under special conditions, as in curved pipes, laminar flow may occur above values of 2,300. A good working rule is to take 2,000 as the dividing line, remembering that the pressure drop computed will be uncertain for values of Reynolds number between 1,200 and 2,300. The magnitude of the uncertainty may be found computing the flow both ways. In the rare instances that this uncertainty is important, texts on hydraulics should be consulted.

As noted under Eq. (F-10), the equivalent diameter is employed for computing the Reynolds number when the cross section is not circular. This is defined as four times the ratio of cross-sectional area of flowing fluid to the wetted perimeter of the channel. The equivalent diameter is four times the hydraulic radius. Table F-4 gives the equivalent diameters for several shapes.

TABLE F-4.—VALUES OF EQUIVALENT DIAMETERS FOR SEVERAL CROSS SECTIONS

$$\text{Equivalent diameter} = \frac{4 \times \text{cross section}}{\text{wetted perimeter}}$$

Shape of Cross Section	Equivalent Diameter
Pipes and ducts running full:	
Circle diameter = D	D
Annulus, inner diameter = d, outer = D	$D - d$
Square, side = D	D
Rectangle, sides = a, b	$\frac{2ab}{a + b}$
Open channels or partly filled ducts:	
Rectangle, depth = D, width = W	$\frac{4WD}{W + 2D}$
Semicircle, free surface on diameter D	D

c. General Method—Turbulent Flow.—The pressure drop produced by turbulent flow of fluids is readily calculated by the Fanning equation which is given below in several forms:

$$\Delta p = \frac{fLG^2}{193\rho d} = \frac{fLu^2\rho}{193d} = \frac{fLW^2}{74{,}000\rho d^5} = \frac{fLm^2\rho'}{155d^5} \qquad \text{(F-11)}$$

where Δp = pressure drop, psi
f = Fanning friction factors (see Figs. F-12 to F-14)
L = length of pipe, ft
G = mass velocity, lb/(sq ft)(sec)
ρ = fluid density, lb/cu ft
ρ' = fluid density, lb/gal
d = inside diameter of pipe, in.
u = average linear velocity, fps
W = flow, lb/hr
m = flow, gpm

This equation gives reliable results for all liquids, including thin slurries, but fails for thick slurries and for semiplastic materials. It may be applied to gases but will be accurate only if Δp is less than 10 per cent of the downstream pressure. However, if average values of the density are used, the equation then gives accurate results when Δp is up to 40 per cent of the downstream pressure.

Numerical values of the friction factor for use in Eq. (F-11) are given in Figs. F-12 to F-14. These figures were constructed almost entirely from data of Pigott and Kemler[1] though factors suggested by

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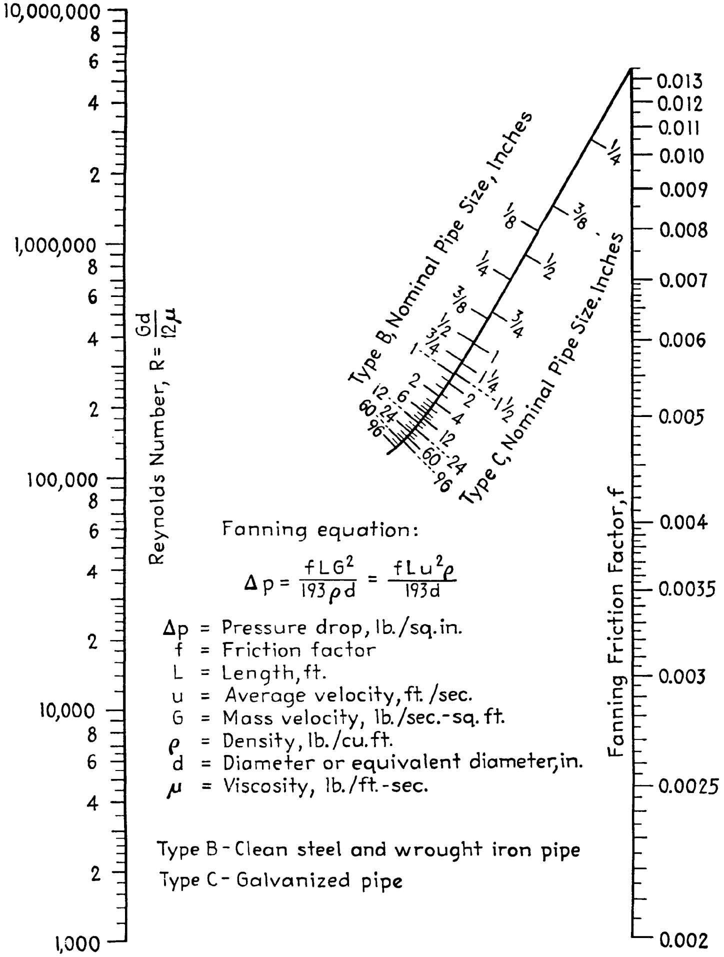
[1] Mech. Eng., **55**, 497 (1933); *Trans. Am. Soc. Mech. Engrs.*, **55**, HYD 55-2 (1933).



Fanning equation:

$$\Delta p = \frac{fLG^2}{193\rho d} = \frac{fLu^2\rho}{193d}$$

Δp = Pressure drop, lb./sq.in.
f = Friction factor
L = Length, ft.
u = Average velocity, ft./sec.
G = Mass velocity, lb./sec.-sq.ft.
ρ = Density, lb./cu.ft.
d = Diameter or equivalent diameter, in.
μ = Viscosity, lb./ft.-sec.

Type B - Clean steel and wrought iron pipe
Type C - Galvanized pipe

FIG. F-12.—Friction factors for pipe, Types B and C.

Drew, Koo, and McAdams[1] on smooth tubes were taken into consideration.

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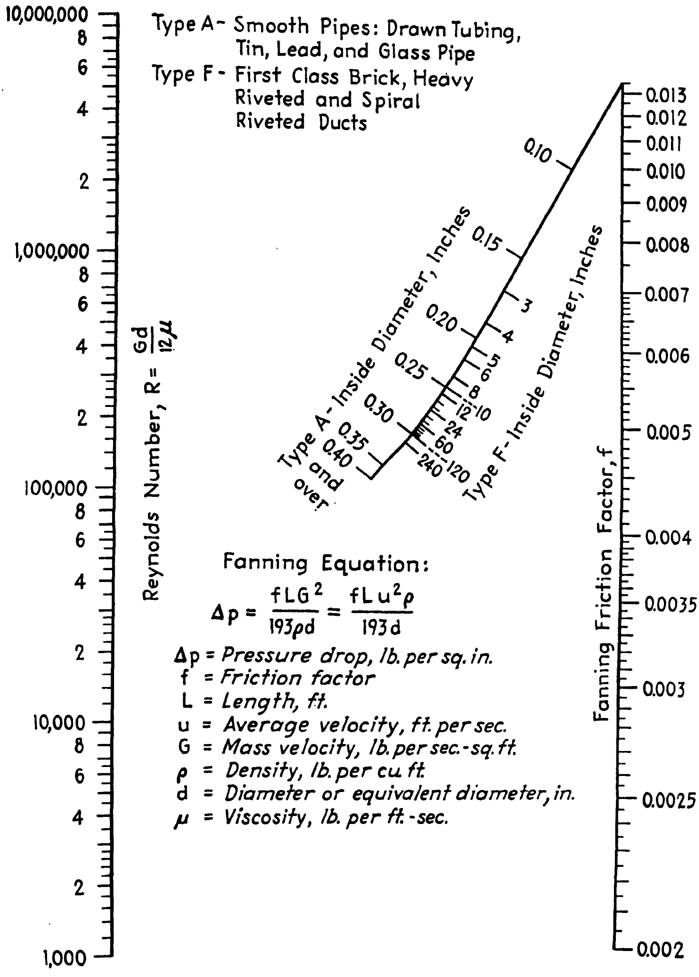
[1] *Trans. Am. Inst. Chem. Engrs.*, **28**, 56 (1933).

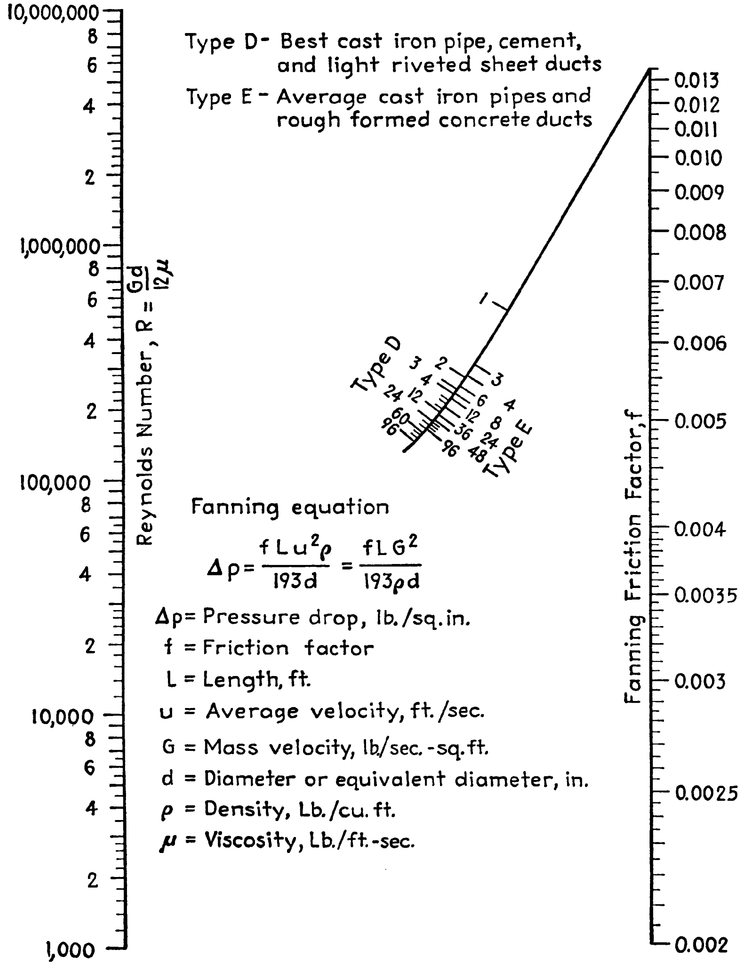


Fanning Equation:

$$\Delta p = \frac{fLG^2}{193\rho d} = \frac{fLu^2\rho}{193d}$$

Δp = *Pressure drop, lb. per sq. in.*
f = *Friction factor*
L = *Length, ft.*
u = *Average velocity, ft. per sec.*
G = *Mass velocity, lb. per sec.-sq. ft.*
ρ = *Density, lb. per cu. ft.*
d = *Diameter or equivalent diameter, in.*
μ = *Viscosity, lb. per ft.-sec.*

Fig. F-13.—Friction factors for pipe, Types A and F.



Type D- Best cast iron pipe, cement, and light riveted sheet ducts

Type E - Average cast iron pipes and rough formed concrete ducts

Fanning equation

$$\Delta p = \frac{fLu^2\rho}{193d} = \frac{fLG^2}{193\rho d}$$

Δp = Pressure drop, lb./sq.in.
f = Friction factor
L = Length, ft.
u = Average velocity, ft./sec.
G = Mass velocity, lb/sec.-sq.ft.
d = Diameter or equivalent diameter, in.
ρ = Density, Lb./cu.ft.
μ = Viscosity, Lb./ft.-sec.

FIG. F-14.—Friction factors for pipe, Types D and E.

d. Special Methods.—The main use of pressure-drop data is selection of the most economic pipe size. Such a choice is dependent on a number of factors, particularly on the relative costs of piping and power. Figure F-15 permits a preliminary choice of pipe size. This chart is based on relative costs typical of the Atlantic seaboard before the war. The basic equation for this chart is given by Drew and Genereaux[1] and the reader may prepare similar charts based on costs and depreciation rates typical of his own cost studies. Usually it will be found that pipe sizes, as read by this chart, may be multiplied by a constant correction factor to secure a result corrected for revised factors. Table F-5 gives typical fluid velocities used in service.

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[1] Perry, *op. cit.*

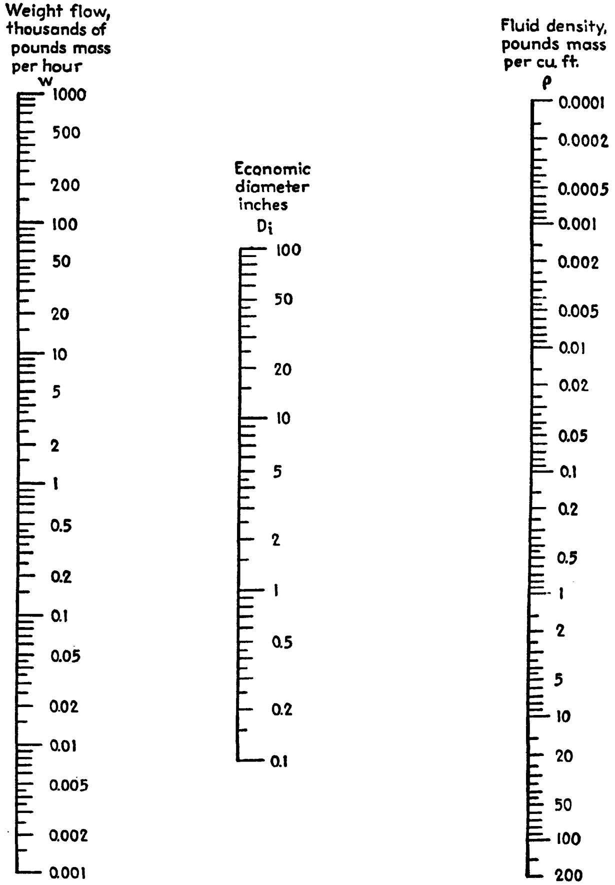

FIG. F-15.—Economic pipe diameters. (*Perry, "Chemical Engineers' Handbook," 2 ed., McGraw-Hill Book Company, Inc., New York,* 1941.)

Tables F-6 to F-15 give the pressure drop in feet of liquid per 1,000 ft of pipe, based on clean steel pipe. The pressure drop in pounds per square inch may be obtained by the following factors:

$$\Delta p = 0.433sh = \frac{\rho h}{144} = \frac{\rho' h}{19.25}$$

where Δp = pressure drop, psi/1,000 ft
s = specific gravity, 60/60
ρ, ρ' = liquid density, lb/cu ft, lb/gal
h = feet of liquid, values given in tables

TABLE F-5.—REASONABLE VELOCITIES OF STEAM AND WATER IN POWER-PLANT PIPING WHERE ACTUAL PRESSURE DROPS ARE NOT COMPUTED
(Sabin Crocker, "Piping Handbook," 4th ed., McGraw-Hill Book Company, Inc., New York, 1945)

Fluid	Pressure, psig	Use	Reasonable velocity, fpm
Water	25–40	City water	120–300
Water	50–150	General service	300–600
Water	150 up	Boiler feed	600
Saturated steam	0–15	Heating	4,000–6,000
Saturated steam	50 up	Miscellaneous	6,000–10,000
Superheated steam	200 up	Large turbine and boiler leads	10,000–15,000

TABLE F-6.—FRICTION LOSSES IN PIPE; 1 IN. (1.049 IN. ID); LOSS IN FEET OF LIQUID PER 1,000 FT OF PIPE
(Reprinted from "Cameron Hydraulic Data," 11th ed., 1942, by permission of Ingersoll-Rand Company)

Flow		Kinematic viscosity, centistokes									
U.S. gpm	Bbl/hr (42 gal)	0.6	1.1	2.1	2.7	4.3	7.4	10.3	13.1	15.7	20.6
		Approx. SSU viscosity									
			31.5	33	35	40	50	60	70	80	100
0.5	0.71	0.07	0.28	0.55	0.70	1.12	1.93	2 68	3.41	4.08	5.35
1	1.4	1.00	1.13	1.09	1.41	2.24	3.86	5.36	6.82	8.16	10.7
2	2.9	3.60	4.02	4.70	4.7	4.48	7.72	10.7	13.6	16.3	21.4
3	4.3	7.50	8.16	9.48	10.2	10.6	11.6	16.1	20.5	24.5	32.1
4	5.7	12.5	14.1	15.7	16.5	18.1	15.4	21.5	27.3	32.6	42.8
5	7.1	18.9	21.4	23.2	24.8	26.5	19.3	26.8	34.1	40.8	53.5
6	8.6	25.7	29.1	32.6	34.5	37.8	41.3	32.2	40.9	49.0	64.2
7	10	34.9	38.5	43.3	45.6	49.5	55.3	37.5	47.7	57.2	74.9
8	11.4	44.5	50.2	55.2	58.3	63.5	70.3	74.2	54.5	65.2	85.6
9	12.9	55.6	61.6	68.6	70.7	78.6	87.3	92.0	61.4	73.4	96.3
10	14.3	69.0	74.8	83.6	87.4	95.0	106	111	118	81.6	107
12	17.1	94.6	103	117	121	133	144	158	166	170	129
14	20.0	127	138	154	161	175	194	208	218	225	150
16	22.8	163	176	196	205	223	247	264	277	285	302
18	25.7	203	220	242	254	277	305	326	340	350	370
20	28.6	247	265	294	308	335	370	392	412	423	448
25	35.7	374	410	442	463	503	552	597	619	638	676
30	42.9	530	575	618	644	698	775	820	865	886	936
35	50.0	703	755	822	858	925					

TABLE F-6.—FRICTION LOSSES IN PIPE; 1 IN. (1.049 IN. ID); LOSS IN FEET OF LIQUID PER 1,000 FT OF PIPE (*Continued*)

Flow		Kinematic viscosity, centistokes									
		26.4	32.0	43.2	65.0	108.4	162.3	216.5	325	435	650
U.S. gpm	Bbl/hr (42 gal)	Approx. SSU viscosity									
		125	150	200	300	500	750	1,000	1,500	2,000	3,000
0.1	0.14	1.37	1.66	2.25	3.38	5.65	8.45	11.3	16.9	22.6	33.8
0.3	0.43	4.12	4.98	6.75	10.2	17.0	25.3	33.8	50.7	67.8	102
0.5	0.71	6.86	8.32	11.3	16.9	28.3	42.3	56.4	85	113	169
1	1.4	13.7	16.6	22.5	33.8	56.5	84.5	113	169	226	338
2	2.9	27.5	33.2	45.0	67.6	113	169	226	338	452	676
3	4.3	41.2	49.8	67.5	102	170	253	338	507	678	
4	5.7	55.0	66.5	90.0	136	226	338	452	677	904	
5	7.1	68.7	83.2	113	169	283	423	564	846		
6	8.6	82.4	99.7	135	203	339	507	677			
7	10	96.2	117	158	237	395	591	790			
8	11.4	110	133	180	271	452	676	903			
9	12.9	124	150	203	303	508	760				
10	14.3	137	167	225	338	565	845				
12	17.1	165	200	270	406	678					
14	20.0	192	233	315	474	792					
16	22.8	220	266	360	541	904					
18	25.7	248	299	405	609						
20	28.6	470	332	450	677						

TABLE F-7.—FRICTION LOSSES IN PIPE; 2 IN. (2.067 IN. ID); LOSS IN FEET OF LIQUID PER 1,000 FT OF PIPE
(Reprinted from "Cameron Hydraulic Data," 11th ed., 1942, by permission of Ingersoll-Rand Company)

Flow		Kinematic viscosity, centistokes									
U.S. gpm	Bbl/hr (42 gal)	0.6	1.1	2.1	2.7	4.3	7.4	10.3	13.1	15.7	20.6
		Approx. SSU viscosity									
			31.5	33	35	40	50	60	70	80	100
1	1.4	0.04	0.04	0.07	0.09	0.15	0.26	0.36	0.45	0.54	0.71
2	2.9	0.13	0.15	0.15	0.19	0.30	0.51	0.71	0.90	1.08	1.42
4	5.7	0.45	0.52	0.60	0.63	0.59	1.02	1.42	1.81	2.17	2.84
6	8.6	0.94	1.07	1.23	1.29	1.43	1.53	2.13	2.71	3.25	4.26
8	11.4	1.56	1.77	2.05	2.16	2.39	2.04	2.84	3.61	4.33	5.68
10	14.3	2.34	2.61	3.04	3.24	3.57	2.56	3.56	4.52	5.42	7.11
12	17.1	3.28	3.70	4.23	4.47	4.90	5.52	4.27	5.43	6.51	8.53
14	20.0	4.33	4.86	5.57	5.90	6.47	7.28	4.98	6.33	7.59	9.96
16	22.8	5.58	6.18	7.10	7.45	8.20	9.23	9.90	7.23	8.67	11.4
18	25.7	6.84	7.60	8.68	9.20	10.2	11.5	12.2	12.8	9.76	12.8
20	28.6	8.33	9.25	10.6	11.1	12.3	13.8	14.7	15.5	10.8	14.2
25	35.7	12.6	14.0	15.7	16.5	18.3	20.6	22.1	23.1	24.2	17.8
30	42.9	17.5	19.3	22.0	22.9	25.3	28.4	30.4	32.1	33.3	35.1
35	50.0	23.5	25.8	28.8	30.4	33.2	37.2	40.1	42.1	43.8	46.6
40	57.1	30.1	32.7	37.0	38.6	42.5	47.6	50.9	53.9	55.6	59.0
50	71.4	45.4	49.5	55.4	57.8	63.5	71.0	76.0	80.1	82.5	87.5
60	85.7	64.2	69.3	77.2	81.0	88.0	98.7	106	110	115	121
70	100	85.5	92.3	102	107	118	130	139	146	151	161
80	114	109	118	130	135	147	165	176	184	190	203
90	129	136	147	162	169	183	203	217	227	236	251
100	143	165	178	198	205	223	244	264	276	287	304
110	157	198	213	236	244	264	292	312	328	340	360
120	171	233	252	276	288	309	342	366	383	397	421
130	186	271	292	318	335	357	396	419	441	458	486
140	200	312	337	368	382	408	453	479	505	524	553
150	214	356	384	419	432	464	513	545	572	594	624
160	228	403	432	474	487	525	578	616	643	567	701
170	243	452	482	532	545	587	645	687	715	744	782
180	257	502	535	591	605	650	716	760	792	824	867
190	271	554	597	653	668	715	789	835	870	906	954
200	286	610	661	718	736	785	860	920	958	995	
210	300	670	728	788	807	860	947				
220	314	735	795	860	880	935					
230	328	795	860	930	960						
240	343	865	935								

TABLE F-7.—FRICTION LOSSES IN PIPE; 2 IN. (2.067 IN. ID); LOSS IN FEET OF LIQUID PER 1,000 FT OF PIPE (*Continued*)

Flow		Kinematic viscosity, centistokes									
U.S. gpm	Bbl/hr (42 gal)	26.4	32.0	43.2	65.0	108.4	162.3	216.5	325	435	650
		Approx. SSU viscosity									
		125	150	200	300	500	750	1,000	1,500	2,000	3,000
1	1.4	0.91	1.10	1.49	2.24	3.74	5.60	7.48	11.2	15.0	22.4
2	2.9	1.82	2.21	2.98	4.48	7.49	11.2	15.0	22.4	30.0	44.9
3	4.3	2.73	3.31	4.47	6.73	11.2	16.8	22.4	33.6	45.0	67.4
4	5.7	3.64	4.42	5.96	8.98	15.0	22.4	29.9	44.8	60.0	89.9
5	7.1	4.56	5.52	7.45	11.2	18.7	28.0	37.4	56.0	75.0	112
6	8.6	5.47	6.63	8.95	13.5	22.5	33.6	44.8	67.2	90.0	135
7	10.0	6.38	7.73	10.4	15.7	26.2	39.2	52.3	78.4	105	157
8	11.4	7.29	8.84	11.9	18.0	30.0	44.8	59.8	89.6	120	180
9	12.9	8.20	9.94	13.4	20.2	33.7	50.4	67.3	101	135	202
10	14.3	9.11	11.0	14.9	22.4	37.4	56.0	74.8	112	150	224
12	17.1	10.9	13.3	17.9	26.9	44.9	67.3	89.7	135	180	269
14	20.0	12.7	15.5	20.9	31.4	52.4	78.4	105	157	210	314
16	22.8	14.6	17.7	23.9	35.9	59.9	89.6	120	179	240	359
18	25.7	16.4	19.9	26.8	40.3	67.4	101	135	202	270	404
20	28.6	18.2	22.1	29.8	44.9	74.9	112	150	224	300	449
25	35.7	22.8	27.6	37.3	56.1	93.6	140	187	280	375	562
30	42.9	27.3	33.1	44.7	67.3	112	168	224	336	450	674
35	50.0	31.9	38.7	52.2	78.5	131	196	262	392	525	786
40	57.1	50.9	44.2	59.6	89.8	150	224	299	448	600	899
45	64.3	70.7	80.4	67.1	101	168	252	336	504	675	
50	71.4	92.5	96.7	74.5	112	187	280	374	560	750	
60	85.7	128	133	143	135	225	336	448	672	900	
70	100	168	175	188	157	262	392	523	784		
80	114	215	224	239	180	300	448	598	896		
90	129	264	275	294	321	337	504	673			
100	143	320	332	354	390	374	560	748			
110	157	380	395	420	460	412	617	823			
120	171	445	462	490	536	449	673	898			
130	186	512	529	566	615	487	728				
140	200	582	608	648	701	524	784				
150	214	661	681	729	795	892	840				
160	228	744	769	818	895	995	896				
170	243	825	858	915	......	......	952				
180	257	910	953								
190	271	999									

TABLE F-8.—FRICTION LOSSES IN PIPES; 3 IN. (3.068 IN. ID); LOSS IN FEET OF LIQUID PER 1,000 FT OF PIPE

(Reprinted from "Cameron Hydraulic Data," 11th ed., 1942, by permission of Ingersoll-Rand Company)

Flow		Kinematic viscosity, centistokes									
		0.6	1.1	2.1	2.7	4.3	7.4	10.3	13.1	15.7	20.6
U.S. gpm	Bbl/hr (42 gal)	Approx. SSU viscosity									
			31.5	33	35	40	50	60	70	80	100
8	11.4	0.24	0.27	0.31	0.33	0.24	0.42	0.59	0.74	0.89	1.18
10	14.3	0.35	0.41	0.46	0.49	0.54	0.53	0.73	0.93	1.11	1.47
15	21.4	0.73	0.83	0.95	1.00	1.11	0.79	1.10	1.40	1.67	2.20
20	28.6	1.25	1.39	1.58	1.67	1.84	2.08	1.46	1.86	2.23	2.93
25	35.7	1.86	2.06	2.38	2.50	2.75	3.10	3.33	2.33	2.79	3.66
30	42.9	2.60	2.88	3.30	3.46	3.79	4.26	4.62	4.82	3.35	4.40
35	50.0	3.43	3.82	4.32	4.55	5.03	5.62	6.05	6.35	6.65	5.13
40	57.1	4.40	4.92	5.50	5.80	6.38	7.13	7.71	8.07	8.53	5.87
50	71.4	6.65	7.35	8.26	8.60	9.52	10.7	11.5	12.0	12.5	13.6
60	85.7	9.40	10.2	11.5	12.0	13.2	14.7	15.8	16.7	17.3	18.5
70	100	12.4	13.6	15.3	15.8	17.3	19.3	20.9	22.0	22.9	24.3
80	114	16.0	17.3	19.4	20.3	22.0	24.6	26.4	27.9	29.0	30.8
90	129	19.9	21.5	23.9	25.2	27.3	30.5	32.7	34.3	35.8	37.9
100	143	24.0	26.1	29.1	30.3	33.0	37.1	39.4	41.3	43.2	45.8
120	171	34.0	37.0	40.7	42.2	46.7	51.8	54.8	57.7	59.7	63.3
140	200	45.8	49.1	54.0	56.2	61.7	67.3	72.1	75.7	79.0	83.6
160	228	58.2	62.8	69.3	71.5	77.5	85.7	91.5	96.4	99.8	106
180	257	72.9	78.7	86.2	89.1	96.3	106	113	119	123	131
200	286	89.0	95.5	104	108	116	128	136	144	149	158
225	322	111	118	130	135	144	160	170	177	185	195
250	357	135	145	158	164	175	192	204	215	224	235
275	393	163	174	188	196	208	229	243	254	264	281
300	429	192	204	223	230	246	268	285	297	309	326
325	464	223	238	259	266	284	310	330	344	358	378
350	500	256	273	296	306	326	354	377	393	407	433
375	536	290	310	335	348	371	403	429	448	464	485
400	571	330	351	378	392	418	455	483	506	522	547
425	607	370	394	424	439	468	508	539	563	579	609
450	643	413	438	473	488	520	563	595	623	441	678
475	679	456	487	523	541	575	624	662	688	708	746
500	714	502	537	576	596	632	686	722	756	780	820
525	750	550	587	632	652	694	748	790	825	853	897
550	786	604	641	688	709	757	817	860	900	930	973
575	822	655	697	749	773	820	887	933	975		
600	857	710	757	810	835	890	960				

TABLE F-8.—FRICTION LOSSES IN PIPES; 3 IN. (3.068 IN. ID); LOSS IN FEET OF LIQUID PER 1,000 FT OF PIPE (*Continued*)

Flow		Kinematic viscosity, centistokes									
U.S. gpm	Bbl/hr (42 gal)	26.4	32.0	43.2	65.0	108.4	162.3	216.5	325	435	650
		Approx. SSU viscosity									
		125	150	200	300	500	750	1,000	1,500	2,000	3,000
4	5.7	0.75	0.91	1.23	1.85	3.08	4.62	6.16	9.25	12.4	18.5
6	8.6	1.13	1.37	1.84	2.77	4.62	6.92	9.24	13.9	18.5	27.7
8	11.4	1.50	1.82	2.45	3.70	6.16	9.23	12.3	18.5	24.7	36.9
10	14.3	1.88	2.28	3.06	4.62	7.70	11.5	15.4	23.1	30.9	46.2
12	17.1	2.25	2.73	3.68	5.55	9.24	13.8	18.5	27.7	37.1	55.5
14	20.0	2.63	3.18	4.29	6.47	10.8	16.2	21.5	32.3	43.3	64.7
16	22.8	3.00	3.64	4.90	7.39	12.3	18.5	24.6	37.0	49.5	73.9
18	25.7	3.38	4.09	5.52	8.31	13.9	20.8	27.7	41.6	55.6	83.2
20	28.6	3.76	4.55	6.13	9.24	15.4	23.1	30.8	46.2	61.8	92.4
25	35.7	4.69	5.69	7.67	11.5	19.3	28.8	38.5	57.7	77.3	115
30	42.9	5.63	6.83	9.20	13.9	23.1	34.6	46.2	69.3	92.7	139
35	50.0	6.57	7.97	10.7	16.2	27.0	40.3	53.8	80.9	108	162
40	57.1	7.51	9.10	12.3	18.5	30.8	46.2	61.6	92.5	124	185
50	71.4	9.39	11.4	15.3	23.1	38.5	57.7	77.0	115	154	231
60	85.7	19.5	13.7	18.4	27.7	46.2	69.2	92.4	139	185	277
70	100	25.4	26.5	21.5	32.3	53.9	80.8	108	162	216	323
80	114	32.3	33.8	24.7	37.0	61.6	92.3	123	185	247	369
90	129	40.0	41.7	44.6	41.6	69.3	104	139	208	278	416
100	143	48.2	50.3	53.7	46.2	77.0	115	154	231	309	462
120	171	66.7	70.0	74.3	55.5	92.4	138	185	277	371	555
140	200	88.0	91.7	98.0	108	108	162	215	323	433	647
160	228	112	116	125	136	123	185	246	370	495	739
180	257	138	144	154	167	139	208	277	416	556	832
200	286	165	174	185	202	154	231	308	462	618	924
225	322	206	214	227	250	279	260	346	520	696	
250	357	249	258	275	301	338	288	385	577	773	
275	393	295	308	326	358	399	317	423	635	850	
300	429	344	359	382	416	462	346	462	693	927	
325	464	397	413	440	479	534	375	500	751		
350	500	452	472	504	548	613	669	538	809		
375	536	515	535	562	619	690	755	577	867		
400	571	579	602	638	696	770	851	616	925		
425	607	642	670	712	778	862	936	654	982		
450	643	715	743	790	865	955					
475	679	787	818	869	949						

TABLE F-9.—FRICTION LOSSES IN PIPE; 4 IN. (4.026 IN. ID); LOSS IN FEET OF LIQUID PER 1,000 FT OF PIPE

(Reprinted from "Cameron Hydraulic Data," 11th ed., 1942, by permission of Ingersoll-Rand Company)

Flow		Kinematic viscosity, centistokes									
U.S. gpm	Bbl/hr (42 gal)	0.6	1.1	2.1	2.7	4.3	7.4	10.3	13.1	15.7	20.6
		Approx. SSU viscosity									
			31.5	33	35	40	50	60	70	80	100
20	28.6	0.32	0.36	0.42	0.44	0.48	0.57	0.50	0.63	0.75	0.99
30	42.9	0.67	0.74	0.86	0.91	0.99	1.16	1.25	0.95	1.13	1.48
40	57.1	1.12	1.24	1.43	1.51	1.64	1.92	2.08	2.20	1.51	1.96
50	71.4	1.69	1.85	2.13	2.23	2.42	2.82	3.06	3.24	3.39	2.47
60	85.7	2.37	2.61	2.96	3.12	3.35	3.90	4.24	4.50	4.67	5.00
70	100	3.14	3.46	3.91	4.09	4.39	5.14	5.55	5.89	6.18	6.53
80	114	4.06	4.42	4.95	5.19	5.57	6.49	7.01	7.43	7.77	8.30
90	129	5.06	5.48	6.09	6.43	6.90	8.02	8.70	9.16	9.55	10.2
100	143	6.12	6.67	7.41	7.76	8.35	9.68	10.4	11.1	11.5	12.3
120	171	8.56	9.31	10.3	10.8	11.6	13.4	14.4	15.3	16.0	17.0
140	200	11.4	12.5	13.7	14.3	15.2	17.5	18.9	19.9	20.8	22.2
160	228	14.6	16.0	17.5	18.4	19.4	22.3	24.0	25.3	26.6	28.1
180	257	18.3	19.8	21.7	22.7	24.0	27.5	29.4	31.0	32.4	34.7
200	286	22.2	24.0	26.5	27.6	29.2	33.3	35.6	37.6	39.1	41.5
220	314	26.6	28.6	31.6	32.8	34.7	39.7	42.2	44.5	46.3	49.4
240	343	31.3	33.8	37.2	38.6	40.7	46.2	48.9	51.6	54.2	57.6
260	371	36.4	39.2	42.5	44.5	47.0	53.4	56.7	59.8	62.1	66.1
280	400	41.8	45.1	49.8	51.2	54.0	61.0	64.8	68.3	71.2	75.2
300	429	47.7	51.3	56.4	58.3	61.4	68.5	73.8	77.5	80.6	85.0
350	500	63.7	68.5	75.0	77.8	81.5	91.1	96.9	102	106	112
400	571	81.9	88.0	95.7	99.9	104	117	123	130	135	142
450	643	103	110	119	123	130	145	153	160	167	176
500	714	125	134	146	150	159	176	185	192	200	212
550	786	150	160	174	179	189	209	221	228	238	250
600	857	176	189	204	210	221	244	259	267	276	293
650	929	204	220	236	244	256	283	299	311	319	339
700	1,000	236	253	272	281	294	325	342	358	366	387
750	1,070	268	287	310	320	334	368	387	404	418	438
800	1,140	302	324	350	361	376	415	437	453	468	490
850	1,215	340	365	392	404	423	464	489	510	524	547
900	1,285	381	405	437	450	470	518	544	563	589	608
950	1,360	423	449	483	497	520	575	600	622	633	670
1,000	1,430	465	494	532	546	575	632	660	685	707	740
1,100	1,570	555	596	639	655	685	754	785	815	842	884
1,200	1,715	661	703	750	772	805	885	925	958	985	

TABLE F-9.—FRICTION LOSSES IN PIPE; 4 IN. (4.026 IN. ID); LOSS IN FEET OF LIQUID PER 1,000 FT OF PIPE (*Continued*)

Flow		Kinematic viscosity, centistokes									
		26.4	32.0	43.2	65.0	108.4	162.3	216.5	325	435	650
U.S gpm	Bbl/hr (42 gal)	Approx. SSU viscosity									
		125	150	200	300	500	750	1,000	1,500	2,000	3,000
15	21.4	0.95	1.15	1.55	2.34	3.91	5.85	7.80	11.7	15.7	23.4
20	28.6	1.27	1.54	2.07	3.12	5.21	7.80	10.4	15.6	20.9	31.2
30	42.9	1.90	2.30	3.11	4.68	7.82	11.7	15.6	23.4	31.3	46.8
40	57.1	2.54	3.08	4.15	6.25	10.4	15.6	20.8	31.2	41.8	62.5
50	71.4	3.17	3.84	5.18	7.81	13.0	19.5	26 0	39.0	52.2	78.1
60	85.7	3.80	4.61	6.22	9.37	15.6	23.4	31.2	46.8	62.7	93.7
70	100	4.44	5.38	7.25	10.9	18.2	27.3	36.4	54.6	73 2	109
80	114	8.83	6.15	8.29	12.5	20.8	31.2	41.6	62.4	83.6	125
90	129	10.8	11.4	9.33	14.1	23.4	35.1	46.8	70.2	94.1	141
100	143	13.0	13.6	10.4	15.6	26.0	39.0	52.0	78.0	105	156
120	171	18.0	18.8	20.2	18.8	31.2	46.8	62.4	93.7	125	187
140	200	23.5	24.7	26.5	21.9	36.4	54.6	72.8	109	146	218
160	228	29.9	31.1	33.8	25.0	41.7	62.4	83.2	125	167	250
180	257	36.6	38.4	41.2	45.5	46.9	70.2	93.6	140	188	281
200	286	44.3	46.3	49.6	54.7	52.1	78.0	104	156	209	312
220	314	52.5	54.8	58.7	64.5	57.3	85.8	114	172	230	343
240	343	61.1	63.8	68.6	76.1	62.5	93.6	125	187	251	375
260	371	70.2	73.3	78.9	87.0	67.7	101	135	203	272	406
280	400	80.0	83.6	90.2	99.3	73.0	109	146	218	292	437
300	429	90.2	94.6	102	112	126	117	156	234	313	468
325	464	104	109	117	128	146	127	169	254	340	508
350	500	118	124	133	147	166	136	182	273	366	547
375	536	134	140	151	166	187	146	195	293	392	585
400	571	151	157	169	186	209	156	208	312	418	625
450	643	186	193	208	229	260	284	234	351	470	703
500	714	224	233	250	277	312	342	260	390	523	781
550	786	263	275	296	326	367	403	286	429	575	860
600	857	309	322	344	382	428	472	505	468	627	937
650	929	358	371	398	438	493	543	583	507	680	
700	1,000	407	426	453	497	564	622	665	546	732	
750	1,070	462	482	511	563	636	700	750	585	784	
800	1,140	519	540	574	631	710	780	838	624	836	
850	1,215	579	601	638	700	793	867	937	663	889	
900	1,285	640	668	708	773	878	965	......	......	941	
950	1,360	703	735	783	852	965	......	......	......	993	

TABLE F-10.—FRICTION LOSSES IN PIPE; 6 IN. (6.065 IN. ID); LOSS IN FEET OF LIQUID PER 1,000 FT OF PIPE

(Reprinted from "Cameron Hydraulic Data," 11th ed., 1942, by permission of Ingersoll-Rand Company)

Flow		Kinematic viscosity, centistokes									
U.S. gpm	Bbl/hr (42 gal)	0.6	1.1	2.1	2.7	4.3	7.4	10.3	13.1	15.7	20.6
		Approx. SSU viscosity									
			31.5	33	35	40	50	60	70	80	100
75	107	0.47	0.53	0.62	0.65	0.73	0.82	0.89	0.94	0.98	
100	143	0.80	0.89	1.03	1.09	1.21	1.37	1.49	1.56	1.64	1.75
125	178	1.21	1.33	1.54	1.64	1.80	2.02	2.18	2.32	2.42	2.59
150	214	1.67	1.85	2.16	2.26	2.49	2.80	3.01	3.21	3.35	3.55
175	250	2.23	2.44	2.76	2.92	3.26	3.67	4.00	4.22	4.38	4.70
200	286	2.86	3.13	3.52	3.71	4.19	4.65	5.03	5.33	5.53	5.96
225	322	3.55	3.92	4.34	4.54	5.15	5.76	6.22	6.53	6.84	7.31
250	357	4.32	4.75	5.27	5.50	6.17	6.94	7.45	7.87	8.26	8.77
275	393	5.17	5.63	6.27	6.55	7.29	8.27	8.84	9.29	9.77	10.3
300	429	6.08	6.63	7.32	7.65	8.46	9.60	10.3	10.9	11.4	12.0
350	500	8.19	8.84	9.76	10.2	11.1	12.7	13.6	14.1	14.9	15.9
400	571	10.5	11.3	12.5	13.0	14.1	16.1	17.2	18.2	19.0	20.1
450	643	13.1	14.1	15.5	16.0	17.5	19.7	21.3	22.4	23.3	24.6
500	714	15.9	17.1	18.8	19.5	21.2	23.7	25.8	26.9	28.1	30.0
550	786	19.3	20.5	22.5	23.4	25.2	28.0	30.5	32.1	33.5	35.4
600	857	22.7	24.1	26.3	27.6	29.5	32.8	35.5	37.7	39.1	41.3
650	929	26.3	28.1	30.5	31.7	34.0	37.8	40.7	43.3	45.1	47.5
700	1,000	30.1	32.3	35.0	36.5	39.0	43.2	46.5	49.5	51.5	54.2
750	1,070	34.3	36.8	39.7	41.3	44.4	48.7	52.2	55.7	58.1	61.5
800	1,140	38.8	41.7	44.8	46.6	50.0	54.8	58.3	62.2	65.0	69.0
900	1,285	48.7	52.2	55.9	57.8	62.7	67.7	72.5	76.3	80.0	85.5
1,000	1,430	59.2	63.8	68.3	70.6	75.9	82.0	87.5	91.9	96.5	103
1,100	1,570	70.8	76.2	81.8	84.8	90.0	98.3	104	108	114	122
1,200	1,715	84.3	89.7	96.2	99.5	105	115	122	127	134	142
1,400	2,000	113	120	129	132	140	153	161	167	175	186
1,600	2,285	146	155	166	171	180	196	206	214	223	233
1,800	2,570	182	192	206	212	224	244	256	265	275	290
2,000	2,860	224	238	252	259	273	294	310	320	334	350
2,200	3,140	268	283	302	309	325	353	371	382	397	415
2,400	3,430	319	332	356	366	384	412	437	450	465	490
2,600	3,710	370	388	414	426	447	479	503	523	535	565
2,800	4,000	428	448	477	492	513	548	577	601	615	643
3,000	4,285	485	512	542	560	587	627	655	682	701	732
3,250	4,640	569	593	633	650	681	730	763	789	819	850
3,500	5,000	657	688	728	750	785	837	875	900	932	967

Table F-10.—Friction Losses in Pipe; 6 in. (6.065 in. ID); Loss in Feet of Liquid per 1,000 ft of Pipe (*Continued*)

Flow		Kinematic viscosity, centistokes									
U.S. gpm	Bbl/hr (42 gal)	26.4	32.0	43.2	65.0	108.4	162.3	216.5	325	435	650
		Approx. SSU viscosity									
		125	150	200	300	500	750	1,000	1,500	2,000	3,000
50	71.4	0.62	0.74	1.00	1.51	2.52	3.78	5.04	7 57	10.1	15.1
75	107	0.92	1.12	1.51	2.27	3.78	5.66	7.56	11.4	15.2	22.7
100	143	1.23	1.49	2.01	3.03	5.05	7.55	10.1	15.1	20.3	30.2
125	178	2.75	1.86	2.51	3.79	6.31	9.45	12.6	18.9	25.3	37.8
150	214	3.79	4.03	3.01	4.54	7.58	11.3	15.1	22.7	30.4	45.4
175	250	4.94	5.21	5.58	5.30	8.84	13.2	17.6	26.5	35.5	53.0
200	286	6.26	6.56	7.05	6.06	10.1	15.1	20.2	30.3	40.5	60.6
225	322	7.76	8.09	8.70	6.82	11.4	17.0	22.7	34.1	45.6	68.1
250	357	9.31	9.74	10.4	7.57	12.6	18.9	25.2	37.8	50.7	75.7
275	393	11.0	11.5	12.4	13.6	13.9	20.8	27.7	41.7	55.8	83.2
300	429	12.9	13.5	14.5	15.9	15.1	22.6	30.2	45.4	60.9	90.8
350	500	16.9	17.7	19.0	20.8	17.7	26.4	35.3	53.0	71.0	106
400	571	21.4	22.3	23.9	26.3	20.2	30.2	40.3	60.6	81.1	121
450	643	26.3	27.4	29.5	32.4	36.6	34.0	45.3	68.2	91.3	136
500	714	31.5	33.0	35.6	39.0	44.1	37.8	50.4	75.7	101	151
550	786	37.2	39.1	41.8	46.2	52.2	41.6	55.4	83.3	112	166
600	857	43.6	45.7	49.0	53.9	61.0	45.3	60.5	90.9	122	182
650	929	50.3	52.6	56.4	62.2	69.9	49.1	65.5	98.5	132	197
700	1,000	57.3	59.8	64.0	70.7	80.0	87.5	70.6	106	142	212
750	1,070	65.0	67.6	72.6	79.9	90.2	99.1	75.6	114	152	227
800	1,140	72.9	75.8	81.6	89.5	100	111	80.6	121	162	242
900	1,285	89.8	93.5	99.5	111	124	137	147	136	183	272
1,000	1,430	109	113	121	134	150	164	176	151	203	302
1,100	1,570	129	134	143	157	177	195	208	167	223	333
1,200	1,715	151	157	166	184	206	226	245	182	243	363
1,400	2,000	199	207	220	241	270	298	320	351	284	424
1,600	2,285	251	261	280	305	342	378	404	446	324	484
1,800	2,570	309	322	344	375	423	465	497	547	589	545
2,000	2,860	370	385	414	456	511	559	598	658	705	605
2,200	3,140	438	457	493	540	603	662	708	780	833	666
2,400	3,430	512	534	574	630	700	771	827	903	980	726
2,600	3,710	590	615	659	723	812	889	950	......	......	787
2,800	4,000	677	703	750	828	923					
3,000	4,285	766	793	847	935						
3,200	4,570	856	890	950							

FIG. F-11.—FRICTION LOSSES IN PIPE; 8 IN. (7.981 IN. ID); LOSS IN FEET OF LIQUID PER 1,000 FT OF PIPE

(Reprinted from "Cameron Hydraulic Data," 11th ed., 1942, by permission of Ingersoll-Rand Company)

Flow		Kinematic viscosity, centistokes									
U.S. gpm	Bbl/hr (42 gal)	0.6	1.1	2.1	2.7	4.3	7.4	10.3	13.1	15.7	20.6
		Approx. SSU viscosity									
			31.5	33	35	40	50	60	70	80	100
150	214	0.45	0.49	0.57	0.61	0.67	0.77	0.82	0.87	0.90	0.96
200	286	0.76	0.83	0.94	1.01	1.12	1.26	1.35	1.45	1.50	1.59
250	357	1.14	1.25	1.41	1.49	1.66	1.85	2.02	2.14	2.21	2.37
300	429	1.60	1.76	1.95	2.04	2.32	2.59	2.77	2.94	3.06	3.26
350	500	2.14	2.33	2.59	2.71	3.02	3.40	3.65	3.86	4.03	4.29
400	571	2.74	2.98	3.29	3.44	3.82	4.30	4.62	4.89	5.11	5.42
450	643	3.43	3.70	4.09	4.29	4.68	5.38	5.72	6.00	6.25	6.70
500	714	4.13	4.50	4.96	5.18	5.67	6.44	6.92	7.26	7.54	8.08
600	857	5.89	6.33	6.97	7.20	7.90	8.86	9.55	10.0	10.4	11.1
700	1,000	7.91	8.48	9.24	9.63	10.4	11.5	12.6	13.3	13.8	14.6
800	1,140	10.2	10.8	11.8	12.3	13.3	14.6	16.0	16.9	17.5	18.5
900	1,285	12.7	13.5	14.6	15.3	16.5	18.1	19.6	20.9	21.6	22.9
1,000	1,430	15.6	16.5	17.9	18.5	20.0	21.9	23.5	25.0	26.1	27.7
1,200	1,715	21.9	23.3	25.2	26.0	28.0	30.5	32.7	34.3	36.0	38.3
1,400	2,000	29.4	31.3	33.5	34.7	37.0	40.3	43.0	45.2	46.9	50.5
1,600	2,285	37.7	40.3	43.3	44.6	47.3	51.7	54.7	57.1	59.3	64.0
1,800	2,570	47.3	50.5	53.8	55.5	58.9	64.2	67.6	71.1	73.5	78.5
2,000	2,860	57.7	61.5	65.9	67.7	71.5	78.4	82.3	86.2	88.5	94.0
2,200	3,140	69.0	73.6	78.6	81.0	85.7	93.1	97.8	102	105	112
2,400	3,430	82.1	86.5	93.0	95.3	101	110	115	120	124	130
2,600	3,710	96.2	101	108	111	117	127	133	138	143	150
2,800	4,000	110	116	124	128	134	145	153	158	163	172
3,000	4,285	126	132	142	146	153	164	173	180	185	195
3,200	4,570	142	150	160	165	173	185	195	203	209	219
3,400	4,860	160	168	179	185	194	207	218	227	233	244
3,600	5,140	179	187	199	205	216	231	243	252	259	271
3,800	5,425	198	207	222	228	239	255	267	278	286	299
4,000	5,715	218	228	244	251	264	281	295	306	314	329
4,500	6,425	278	288	305	313	331	351	366	382	391	409
5,000	7,145	338	352	372	383	404	428	447	462	476	495
5,500	7,855	408	423	445	458	483	513	534	550	569	593
6,000	8,570	478	499	526	540	568	603	628	647	665	694
6,500	9,280	561	584	613	627	658	699	731	752	772	806
7,000	10,000	650	674	707	721	760	807	838	864	886	923
7,500	10,700	743	768	806	822	866	920	953	982		

TABLE F-11.—FRICTION LOSSES IN PIPE; 8 IN. (7.981 IN. ID); LOSS IN FEET OF LIQUID PER 1,000 FT OF PIPE (*Continued*)

Flow		Kinematic viscosity, centistokes									
		26.4	32.0	43.2	65.0	108.4	162.3	216.5	325	4.35	650
U.S. gpm	Bbl/hr (42 gal)	Approx. SSU viscosity									
		125	150	200	300	500	750	1,000	1,500	2,000	3,000
50	71.4	0.21	0.25	0.34	0.50	0.84	1.26	1.68	2.52	3.38	5.05
100	143	0.41	0.50	0.67	1.01	1.68	2.52	3.36	5 04	6.76	10.1
150	214	1.02	0.75	1.01	1.51	2.52	3.78	5.04	7.56	10.1	15.1
200	286	1.69	1.78	1.34	2.02	3.37	5.04	6.72	10.1	13.5	20.2
250	357	2.50	2.64	2.81	2.52	4.21	6.30	8.40	12.6	16.9	25.2
300	429	3.46	3.63	3.89	3.03	5.05	7.56	10.1	15.1	20.3	30.3
350	500	4.55	4.77	5.09	5.66	5.89	8.82	11.8	17.7	23.6	35.3
400	571	5.78	6.03	6.46	7.10	6.73	10.1	13.5	20.2	27.0	40.4
450	643	7.09	7.40	7.95	8.76	7.58	11.3	15.1	22.7	30.4	45.4
500	714	8.55	8.94	9.58	10.6	8.42	12.6	16.8	25.2	33.8	50.5
550	786	10.1	10.5	11.3	12.5	9.26	13.9	18.5	27.8	37.2	55.5
600	857	11.8	12.3	13.2	14.5	16.5	15.1	20.2	30.3	40.5	60.6
700	1,000	15.5	16.2	17.3	19.1	21.6	17.6	23.5	35.3	47.3	70.6
800	1,140	19.6	20.4	21.9	24.2	27.3	20.1	26.9	40.3	54.0	80.7
900	1,285	24.0	25.2	26.9	29.8	33.5	37.1	30.2	45.4	60.8	90.8
1,000	1,430	29.2	30.4	32.7	36.0	40.4	44.6	33.6	50.4	67.6	101
1,200	1,715	40.4	42.1	44.9	49.3	55.9	61.5	65.9	60.5	81.0	121
1,400	2,000	53.2	55.4	58.9	64.9	73.5	80.7	86.8	70.6	94.5	141
1,600	2,285	67.9	69.9	74.8	82.2	92.5	103	109	80.7	108	161
1,800	2,570	83.5	87.0	92.2	101	114	125	134	148	122	182
2,000	2,860	100	105	112	122	138	151	162	178	135	202
2,200	3,140	118	125	132	143	163	179	191	210	149	222
2,400	3,430	137	145	155	168	190	208	222	246	264	242
2,600	3,710	157	166	179	195	218	240	257	282	304	262
2,800	4,000	181	190	203	222	249	274	293	323	346	282
3,000	4,285	204	213	230	251	280	310	332	364	390	303
3,200	4,570	228	238	258	282	315	346	370	406	437	323
3,400	4,860	256	267	287	314	351	385	413	454	489	343
3,600	5,140	284	295	315	349	389	426	455	501	540	593
3,800	5,425	314	325	348	386	428	468	501	553	593	651
4,000	5,715	345	356	379	425	468	514	551	605	647	711
4,500	6,425	425	441	468	523	577	631	674	745	796	876
5,000	7,145	515	533	568	625	701	760	817	895	962	
5,500	7,855	617	635	670	733	826	898	967			
6,000	8,570	720	742	785	859	970					

TABLE F-12.—FRICTION LOSSES IN PIPE; 10 IN. (10.02 IN. ID); LOSS IN FEET OF LIQUID PER 1,000 FT OF PIPE

(Reprinted from "Cameron Hydraulic Data," 11th ed., 1942, by permission of Ingersoll-Rand Company)

Flow		Kinematic viscosity, centistokes									
U.S. gpm	Bbl/hr (42 gal)	0.6	1.1	2.1	2.7	4.3	7.4	10.3	13.1	15.7	20.6
		Approx. SSU viscosity									
			31.5	33	35	40	50	60	70	80	100
400	571	0.91	0.99	1.10	1.15	1.29	1.45	1.56	1.66	1.72	1.83
500	714	1.37	1.50	1.65	1.73	1.91	2.16	2.31	2.46	2.56	2.71
600	857	1.93	2.09	2.31	2.40	2.62	3.02	3.21	3.37	3.53	3.75
700	1,000	2.59	2.78	3.08	3.20	3.45	3.93	4.23	4.47	4.64	4.93
800	1,140	3.34	3.56	3.94	4.10	4.42	4.90	5.37	5.68	5.87	6.24
900	1,285	4.18	4.44	4.89	5.10	5.50	6.10	6.65	7.00	7.20	7.69
1,000	1,430	5.09	5.42	5.92	6.15	6.62	7.34	8.02	8.44	8.75	9.27
1,100	1,570	6.10	6.50	7.04	7.35	7.90	8.72	9.40	10.0	10.4	11.0
1,200	1,715	7.18	7.64	8.27	8.60	9.23	10.2	10.9	11.7	12.2	12.9
1,300	1,855	8.34	8.94	9.60	10.0	10.7	11.8	12.6	13.4	14.0	14.8
1,400	2,000	9.63	10.3	11.1	11.5	12.3	13.5	14.4	15.3	16.0	16.9
1,500	2,140	11.0	11.7	12.6	13.0	14.0	15.3	16.3	17.2	18.0	19.1
1,600	2,285	12.3	13.2	14.2	14.7	15.8	17.2	18.3	19.3	20.2	21.4
1,800	2,570	15.5	16.5	17.7	18.3	19.6	21.3	22.7	23.8	24.8	26.6
2,000	2,860	18.7	20.2	21.7	22.3	23.8	25.9	27.4	28.6	29.7	32.0
2,200	3,140	22.6	24.2	25.9	26.6	28.3	30.8	32.6	34.0	35.2	37.6
2,400	3,430	26.7	28.4	30.5	31.2	33.4	36.2	38.1	39.7	41.1	43.7
2,600	3,710	31.1	33.1	35.4	36.5	38.8	42.1	44.3	46.0	47.5	50.3
2,800	4,000	35.8	38.0	40.7	42.0	44.4	48.3	50.8	52.8	54.6	57.5
3,000	4,285	41.0	43.2	46.5	47.9	50.5	54.7	57.7	59.8	62.0	64.9
3,500	5,000	55.3	57.8	62.5	64.0	67.2	72.6	77.1	79.5	81.7	86.0
4,000	5,715	71.4	74.8	80.2	82.5	86.6	92.7	98.3	102	105	110
4,500	6,430	89.4	93.7	100	103	108	116	122	126	130	136
5,000	7,145	110	115	122	126	132	141	148	154	158	165
5,500	7,855	131	138	146	150	157	168	176	183	188	196
6,000	8,570	155	163	173	178	186	198	207	215	221	230
6,500	9,280	181	190	200	206	217	230	240	248	255	267
7,000	10,000	209	219	230	237	250	265	277	285	293	307
7,500	10,700	239	250	263	270	284	301	314	323	333	348
8,000	11,400	271	283	297	305	322	340	354	364	375	391
8,500	12,100	305	318	334	341	361	382	397	409	420	437
9,000	12,900	342	355	373	381	401	426	442	456	467	485
10,000	14,300	420	433	456	466	491	520	540	555	567	591
11,000	15,700	507	520	550	560	586	625	647	664	678	705
12,000	17,150	603	616	650	660	692	735	761	780	799	828

TABLE F-12.—FRICTION LOSSES IN PIPE; 10 IN. (10.02 IN. ID); LOSS IN FEET OF LIQUID PER 1,000 FT OF PIPE (*Continued*)

Flow		Kinematic viscosity, centistokes									
U.S. gpm	Bbl/hr (42 gal)	26.4	32.0	43.2	65.0	108.4	162.3	216.5	325	435	650
		Approx. SSU viscosity									
		125	150	200	300	500	750	1,000	1,500	2,000	3,000
150	214	0.25	0.30	0.40	0.61	1.02	1.52	2.03	3.04	4.08	6.09
200	286	0.57	0.40	0.54	0.81	1.35	2.03	2.71	4.06	5.43	8.12
300	429	1.17	1.22	1.31	1.22	2.03	3.04	4.06	6.09	8.15	12.2
400	571	1.95	2.03	2.19	1.62	2.71	4.06	5.41	8.12	10.9	16.2
500	714	2.89	3.02	3.23	3.57	3.39	5.07	6.77	10.1	13.6	20.3
600	857	3.99	4.17	4.48	4.93	4.06	6.08	8.12	12.2	16.3	24.4
700	1,000	5.21	5.47	5.87	6.47	4.74	7.10	9.47	14.2	19.0	28.4
800	1,140	6.62	6.95	7.42	8.13	9.25	8.12	10.8	16.2	21.7	32.5
900	1,285	8.10	8.53	9.14	10.1	11.3	9.13	12.2	18.3	24.5	36.5
1,000	1,430	9.85	10.3	11.0	12.1	13.7	10.1	13.5	20.3	27.2	40.6
1,100	1,570	11.6	12.1	13.0	14.3	16.2	17.9	14.9	22.3	29.9	44.6
1,200	1,715	13.5	14.1	15.2	16.7	18.8	20.8	16.2	24.4	32.6	48.7
1,300	1,855	15.6	16.3	17.5	19.2	21.7	23.9	17.6	26.4	35.3	52.8
1,400	2,000	17.9	18.6	19.9	22.0	24.7	27.3	18.9	28.4	38.0	56.8
1,500	2,140	20.2	21.1	22.5	24.9	28.0	30.8	33.0	30.4	40.8	60.9
1,600	2,285	22.7	23.7	25.2	27.8	31.3	34.4	37.0	32.4	43.5	64.9
1,800	2,570	28.0	29.1	31.1	34.2	38.5	42.3	45.4	36.5	48.9	73.1
2,000	2,860	33.9	35.2	37.5	41.1	46.3	50.8	54.8	40.6	54.3	81.2
2,200	3,140	40.0	41.8	44.3	48.9	55.0	60.3	64.5	71.5	59.8	89.3
2,400	3,430	46.8	49.0	52.0	56.8	63.9	70.5	75.3	83.1	65.2	97.4
2,600	3,710	53.7	56.3	60.0	65.5	73.5	81.3	86.8	95.8	70.7	105
2,800	4,000	60.9	64.3	68.5	74.5	84.2	92.7	98.8	109	76.1	114
3,000	4,285	68.7	72.7	77.6	84.4	94.9	105	112	123	132	122
3,500	5,000	90.7	95.2	103	111	125	137	147	162	174	142
4,000	5,715	114	119	129	141	158	174	185	203	219	162
4,500	6,430	142	148	159	175	195	214	228	252	270	297
5.000	7,145	172	179	191	211	234	257	276	303	324	357
5,500	7,855	205	213	226	250	278	305	326	358	382	421
6,000	8,570	239	248	262	292	325	355	380	418	447	493
6,500	9,280	277	286	304	336	375	409	438	480	515	567
7,000	10,000	317	326	347	381	429	465	499	549	586	646
7,500	10,700	360	370	394	430	485	527	562	621	665	729
8,000	11,400	406	418	442	479	545	592	631	695	743	813
9,000	12,900	508	522	549	594	672	731	779	858	920	
10,000	14,300	615	634	665	715	813	884	937			

TABLE F-13.—FRICTION LOSSES IN PIPE; 12 IN. (12 IN. ID); LOSS IN FEET OF LIQUID PER 1,000 FT OF PIPE
(Reprinted from "Cameron Hydraulic Data," 11th ed., 1942, by permission of Ingersoll-Rand Company)

Flow		Kinematic viscosity, centistokes									
		0.6	1.1	2.1	2.7	4.3	7.4	10.3	13.1	15.7	20.6
U.S. gpm	Bbl/hr (42 gal)	Approx. SSU viscosity									
			31.5	33	35	40	50	60	70	80	100
300	429	0.22	0.24	0.27	0.29	0.33	0.37	0.40	0.42	0.44	0.47
400	571	0.38	0.41	0.46	0.49	0.54	0.61	0.66	0.70	0.73	0.78
500	714	0.57	0.63	0.69	0.73	0.81	0.91	0.98	1.04	1.07	1.15
600	857	0.80	0.87	0.96	1.01	1.12	1.26	1.35	1.43	1.49	1.58
700	1,000	1.07	1.15	1.28	1.34	1.46	1.67	1.77	1.87	1.96	2.08
800	1,140	1.38	1.48	1.64	1.71	1.86	2.11	2.27	2.39	2.47	2.64
900	1,285	1.73	1.85	2.04	2.12	2.30	2.59	2.80	2.96	3.07	3.24
1,000	1,430	2.10	2.25	2.48	2.57	2.78	3.11	3.40	3.57	3.70	3.90
1,200	1,715	2.97	3.17	3.46	3.60	3.87	4.32	4.68	4.94	5.11	5.41
1,400	2,000	3.98	4.24	4.61	4.81	5.14	5.65	6.08	6.49	6.76	7.16
1,600	2,285	5.12	5.48	5.89	6.12	6.58	7.20	7.68	8.20	8.57	9.08
1,800	2,570	6.40	6.81	7.34	7.59	8.18	8.92	9.52	10.0	10.5	11.2
2,000	2,860	7.82	8.34	8.97	9.25	9.97	10.8	11.5	12.0	12.6	13.5
2,500	3,570	11.9	12.7	13.6	14.1	15.0	16.3	17.2	18.0	18.7	20.0
3,000	4,285	16.8	18.0	19.3	19.9	21.0	23.0	24.1	25.2	25.9	27.4
3,500	5,000	22.7	24.1	25.7	26.4	28.0	30.4	31.9	33.1	34.3	36.2
4,000	5,715	29.4	30.9	33.1	34.1	36.0	38.8	40.8	42.4	43.7	46.0
4,500	6,430	36.7	38.6	41.5	42.6	44.8	48.3	50.8	52.7	54.2	56.9
5,000	7,145	45.0	47.2	50.6	52.0	54.8	58.4	61.7	64.0	65.7	68.8
5,500	7,855	54.2	56.7	60.5	62.0	65.5	69.7	73.5	76.5	78.7	82.0
6,000	8,570	64.0	67.0	71.5	73.5	77.3	82.3	86.3	90.0	92.0	96.3
6,500	9,280	74.5	78.2	83.2	85.5	90.0	95.5	99.5	104	107	112
7,000	10,000	86.0	90.1	95.6	98.1	103	110	114	119	123	128
7,500	10,700	98.5	103	109	112	118	126	130	135	139	145
8,000	11,400	111	116	123	127	134	142	147	152	157	164
9,000	12,850	140	146	154	158	166	176	183	189	195	203
10,000	14,300	172	179	188	193	203	215	223	230	236	247
11,000	15,700	208	216	226	231	243	257	366	275	282	294
12,000	17,150	245	254	266	272	286	303	314	324	332	345
13,000	18,550	287	297	312	318	333	353	366	376	385	399
14,000	20,000	332	342	360	360	383	405	422	433	442	458
15,000	21,400	380	390	410	417	437	462	480	494	503	522
16,000	22,850	432	443	465	474	494	524	543	557	570	589
18,000	25,700	545	558	584	595	615	653	679	697	711	733
20,000	28,600	670	684	713	728	755	800	828	853	868	893

TABLE F-13.—FRICTION LOSSES IN PIPE; 12 IN. (12 IN. ID); LOSS IN FEET OF LIQUID PER 1,000 FT OF PIPE (*Continued*)

Flow		Kinematic viscosity, centistokes									
		26.4	32.0	43.2	65.0	108.4	162.3	216.5	325	435	650
U.S. gpm	Bbl/hr (42 gal)	Approx. SSU viscosity									
		125	150	200	300	500	750	1,000	1,500	2,000	3,000
100	143	0.08	0.10	0.13	0.20	0.33	0.49	0.66	0.99	1.32	1.98
200	286	0.16	0.20	0.26	0.39	0.66	0.99	1.32	1.97	2.64	3.95
300	429	0.50	0.55	0.39	0.59	0.99	1.48	1.97	2.96	3.96	5.93
400	571	0.82	0.86	0.93	0.79	1.32	1.98	2.63	3.95	5.28	7.91
500	714	1.22	1.28	1.39	0.99	1.65	2.47	3.27	4.93	6.60	9.89
600	857	1.69	1.76	1.89	1.99	1.98	2.96	3.95	5.92	7.93	11.9
700	1,000	2.22	2.32	2.47	2.74	2.30	3.45	4.61	6.90	9.25	13.8
800	1,140	2.80	2.91	3.14	3.46	2.63	3.95	5.26	7.89	10.6	15.8
900	1,285	3.44	3.61	3.88	4.26	4.82	4.44	5.93	8.88	11.9	17.8
1,000	1,430	4.15	4.35	4.65	5.13	5.80	4.93	6.58	9.87	13.2	19.8
1,200	1,715	5.75	5.99	6.43	7.07	8.00	5.92	7.90	11.8	15.9	23.7
1,400	2,000	7.46	7.85	8.43	9.32	10.5	11.5	9.21	13.8	18.5	27.7
1,600	2,285	9.58	9.98	10.7	11.8	13.2	14.5	10.5	15.8	21.1	31.6
1,800	2,570	11.8	12.3	13.1	14.5	16.3	18.0	13.3	17.7	23.8	35.6
2,000	2,860	14.2	14.8	15.8	17.4	19.7	21.6	23.2	19.7	26.4	39.5
2,500	3,570	21.2	22.1	23.5	25.9	29.2	32.0	34.7	24.6	33.0	49.4
3,000	4,285	29.3	30.6	32.6	35.5	40.2	44.2	47.3	52.0	39.6	59.3
3,500	5,000	38.3	40.4	43.0	46.1	52.7	58.2	62.3	68.7	73.5	69.2
4,000	5,715	48.2	50.6	54.6	59.5	66.8	73.2	78.8	86.3	92.5	79.1
4,500	6,430	59.8	62.3	67.4	73.4	82.2	90.4	97.1	106	114	89.0
5,000	7,145	72.1	75.0	81.2	88.8	98.7	109	117	128	138	98.9
5,500	7,855	86.1	89.3	95.6	106	117	129	138	151	163	178
6,000	8,570	101	104	111	123	137	150	161	177	190	208
6,500	9,280	116	120	128	142	159	173	186	204	218	239
7,000	10,000	132	138	147	162	181	197	211	232	248	274
7,500	10,700	150	156	166	183	204	222	238	263	280	309
8,000	11,400	170	176	186	204	229	249	266	295	314	345
9,000	12,850	211	217	230	251	284	308	326	362	389	426
10,000	14,300	255	264	278	301	342	372	395	435	470	513
11,000	15,700	306	315	331	358	406	442	467	515	551	606
12,000	17,150	360	370	387	418	474	515	548	602	645	708
13,000	18,550	415	430	448	481	543	593	634	693	744	816
14,000	20,000	476	491	515	551	618	682	725	789	844	932
15,000	21,400	540	558	585	625	696	771	816	891	956	
16,000	22,850	609	629	656	705	780	860	916	999		

TABLE F-14.—FRICTION LOSSES IN PIPE; 16 IN. (15.25 IN. ID); LOSS IN FEET OF LIQUID PER 1,000 FT OF PIPE

(Reprinted from "Cameron Hydraulic Data," 11th ed., 1942, by permission of Ingersoll-Rand Company)

Flow		Kinematic viscosity, centistokes									
U.S. gpm	Bbl/hr (42 gal)	0.6	1.1	2.1	2.7	4.3	7.4	10.3	13.1	15.7	20.6
		Approx. SSU viscosity									
			31.5	33	35	40	50	60	70	80	100
600	857	0.25	0.27	0.30	0.32	0.36	0.40	0.43	0.46	0.48	0.51
700	1,000	0.33	0.36	0.40	0.42	0.47	0.53	0.56	0.60	0.62	0.67
800	1,140	0.43	0.46	0.51	0.54	0.59	0.67	0.72	0.76	0.79	0.85
900	1,285	0.54	0.58	0.64	0.67	0.73	0.83	0.89	0.93	0.97	1.04
1,000	1,430	0.65	0.70	0.77	0.81	0.88	1.00	1.07	1.13	1.17	1.25
1,200	1,715	0.92	0.98	1.09	1.13	1.22	1.37	1.49	1.56	1.62	1.73
1,400	2,000	1.23	1.32	1.44	1.51	1.62	1.79	1.95	2.07	2.14	2.27
1,600	2,285	1.58	1.70	1.84	1.92	2.05	2.28	2.47	2.63	2.71	2.87
1,800	2,570	1.98	2.11	2.28	2.38	2.55	2.81	3.03	3.22	3.37	3.56
2,000	2,860	2.41	2.58	2.78	2.89	3.10	3.41	3.63	3.86	4.05	4.28
2,200	3,140	2.90	3.09	3.32	3.44	3.72	4.05	4.31	4.56	4.79	5.11
2,400	3,430	3.42	3.64	3.91	4.04	4.35	4.75	5.05	5.30	5.56	5.95
2,600	3,710	3.98	4.23	4.55	4.70	5.04	5.46	5.80	6.11	6.40	6.86
2,800	4,000	4.55	4.86	5.22	5.39	5.78	6.27	6.69	7.00	7.27	7.84
3,000	4,285	5.19	5.55	5.96	6.15	6.55	7.13	7.60	7.90	8.21	8.83
3,500	5,000	7.00	7.42	7.95	8.20	8.70	9.47	10.0	10.4	10.8	11.5
4,000	5,715	8.99	9.57	10.3	10.6	11.2	12.2	12.8	13.3	13.8	14.6
4,500	6,430	11.3	11.9	12.8	13.1	13.9	15.1	15.9	16.5	17.1	18.0
5,000	7,145	13.9	14.6	15.7	16.2	17.0	18.4	19.3	20.0	20.7	21.7
6,000	8,570	19.7	20.6	22.1	22.7	23.9	25.5	27.1	27.9	28.8	30.5
7,000	10,000	26.5	27.7	29.6	30.3	31.9	34.0	35.9	37.3	38.4	40.0
8,000	11,400	34.2	35.7	38.1	39.0	41.2	43.8	45.9	47.6	49.3	51.1
9,000	12,850	42.9	44.9	47.6	48.8	51.3	54.7	57.0	59.2	61.1	63.5
10,000	14,300	52.7	55.1	57.9	59.7	62.6	66.4	69.5	71.9	74.0	77.0
12,000	17,150	75.0	78.3	82.0	84.3	88.6	94.1	97.8	101	103	108
14,000	20,000	101	105	110	113	119	126	130	134	137	143
16,000	22,850	131	136	143	146	153	162	168	173	177	184
18,000	25,700	166	171	179	182	190	202	210	215	220	228
20,000	28,600	204	209	219	223	232	248	257	262	268	277
22,500	32,200	257	263	275	280	290	309	320	328	335	346
25,000	35,700	315	323	338	344	355	377	390	401	409	422
27,500	39,300	380	389	405	412	425	451	467	480	489	505
30,000	42,850	450	462	479	488	503	531	549	566	576	595
32,500	46,500	526	543	558	568	590	620	640	659	670	691
35,000	50,000	609	629	644	656	680	711	738	757	773	796

TABLE F-14.—FRICTION LOSSES IN PIPE; 16 IN. (15.25 IN. ID); LOSS IN FEET OF LIQUID PER 1,000 FT OF PIPE (*Continued*)

Flow		Kinematic viscosity, centistokes									
		26.4	32.0	43.2	65.0	108.4	162.3	216.5	325	435	650
U.S. gpm	Bbl/hr (42 gal)	Approx. SSU viscosity									
		125	150	200	300	500	750	1,000	1,500	2,000	3,000
400	571	0.26	0.28	0.20	0.30	0.51	0.76	1.01	1.52	2.02	3.03
500	714	0.39	0.41	0.44	0.38	0.63	0.95	1.26	1.89	2.53	3.79
600	857	0.54	0.56	0.61	0.45	0.76	1.14	1.51	2.27	3.04	4.55
700	1,000	0.71	0.74	0.79	0.87	0.89	1.32	1.76	2.65	3.55	5.30
800	1,140	0.89	0.94	1.00	1.11	1.01	1.51	2.02	3.03	4.06	6.06
900	1,285	1.10	1.15	1.23	1.36	1.14	1.70	2.27	3.41	4.56	6.82
1,000	1,430	1.32	1.38	1.49	1.63	1.26	1.89	2.52	3.79	5.07	7.57
1,200	1,715	1.82	1.91	2.05	2.24	2.54	2.27	3.02	4.55	6.08	9.10
1,400	2,000	2.39	2.50	2.69	2.96	3.34	2.65	3.53	5.30	7.10	10.6
1,600	2,285	3.03	3.17	3.40	3.75	4.22	3.03	4.03	6.06	8.11	12.1
1,800	2,570	3.72	3.91	4.19	4.60	5.22	5.74	4.54	6.82	9.12	13.6
2,000	2,860	4.52	4.74	5.06	5.56	6.27	6.90	5.04	7.58	10.1	15.1
2,200	3,140	5.36	5.61	5.98	6.56	7.40	8.17	8 75	8.33	11.2	16.7
2,400	3,430	6.25	6.52	6.95	7.65	8.66	9.55	10.2	9.09	12.2	18.2
2,600	3,710	7.23	7.53	8.00	8.82	9.99	10.9	11.7	9.85	13.2	19.7
2,800	4,000	8.27	8.60	9.10	10.0	11.3	12.4	13.3	10.6	14.2	21.2
3,000	4,285	9.36	9.71	10.3	11.4	12.8	14.0	15.1	11.4	15.2	22.7
3,500	5,000	12.3	12.8	13.6	14.9	16.8	18.4	19.8	21.8	17.7	26.5
4,000	5,715	15.5	16.2	17.3	18.9	21.2	23.3	25.1	27.8	20.3	30.3
4,500	6,430	19.0	20.0	21.4	23.2	26.3	28.7	30.8	33.9	36.4	34.1
5,000	7,145	22.8	24.0	25.8	28.1	31.6	34.6	37.0	40.7	43.7	37.9
6,000	8,570	31.6	32.9	35.7	39.0	43.5	47.8	51.2	56.5	60.5	45.5
7,000	10,000	42.0	43.6	46.5	51.6	56.8	62.7	67.2	74.0	79.3	87.5
8,000	11,400	53.1	55.3	58.9	65.2	72.4	79.5	84.8	93.5	100	110
9,000	12,850	66.0	68.4	72.6	80.5	89.6	97.5	105	115	123	136
10,000	14,300	80.2	83.0	87.5	96.4	108	118	127	139	149	163
12,000	17,150	112	115	122	132	150	163	174	191	205	226
14,000	20,000	149	154	162	174	198	215	227	251	269	296
16,000	22,850	191	197	206	222	250	274	290	318	339	374
18,000	25,700	237	244	255	274	306	337	358	391	420	461
20,000	28,600	288	296	309	331	367	407	433	471	506	555
22,500	32,200	358	368	387	412	455	504	534	580	620	687
25,000	35,700	435	448	470	499	548	604	648	705	752	825
27,500	39,300	520	535	560	594	650	711	763	834	888	975
30,000	42,850	610	627	655	696	761	827	895	975		

TABLE F-15.—FRICTION LOSSES IN PIPE; 20 IN. (19.182 IN. ID); LOSS IN FEET OF LIQUID PER 1,000 FT OF PIPE
(Reprinted from "Cameron Hydraulic Data," 11th ed., 1942, by permission of Ingersoll-Rand Company)

Flow		Kinematic viscosity, centistokes									
U.S. gpm	Bbl/hr (42 gal)	0.6	1.1	2.1	2.7	4.3	7.4	10.3	13.1	15.7	20.6
		Approx. SSU viscosity									
			31.5	33	35	40	50	60	70	80	100
1,000	1,430	0.21	0.23	0.25	0.27	0.29	0.33	0.36	0.38	0.39	0.42
1,500	2,140	0.46	0.49	0.54	0.56	0.61	0.68	0.74	0.78	0.81	0.85
2,000	2,860	0.79	0.84	0.92	0.95	1.03	1.13	1.23	1.30	1.34	1.43
3,000	4,285	1.69	1.81	1.94	2.01	2.16	2.36	2.50	2.64	2.76	2.98
4,000	5,715	2.91	3.11	3.34	3.45	3.68	3.99	4.21	4.41	4.59	4.90
5,000	7,145	4.47	4.76	5.11	5.25	5.55	6.05	6.35	6.60	6.83	7.21
6,000	8,670	6.36	6.72	7.22	7.41	7.80	8.45	8.86	9.24	9.49	10.0
7,000	10,000	8.55	8.97	9.63	9.90	10.4	11.2	11.8	11.2	12.6	13.2
8,000	11,400	11.1	11.6	12.4	12.8	13.4	14.3	15.1	15.7	16.1	16.9
9,000	12,850	13.9	14.5	15.5	15.9	16.7	17.8	18.8	19.5	20.2	20.9
10,000	14,300	17.0	17.7	18.9	19.4	20.4	21.7	22.7	23.7	24.4	25.4
11,000	15,700	20.4	21.3	22.6	23.2	24.4	26.1	27.1	28.2	29.0	30.2
12,000	17,150	24.1	25.2	26.7	27.4	28.8	30.7	32.0	33.2	34.1	35.4
13,000	18,550	28.2	29.5	31.0	31.9	33.5	35.6	37.1	38.4	39.4	41.3
14,000	20,000	32.4	34.0	35.7	36.7	38.5	41.0	42.6	44.0	45.2	47.3
15,000	21,400	37.0	38.8	40.8	41.9	44.0	46.7	48.5	50.0	51.4	53.8
16,000	22,850	42.0	43.9	46.0	47.2	49.7	52.7	54.6	56.3	57.8	60.5
18,000	25,700	53.2	55.1	57.6	59.0	62.0	66.0	68.3	70.5	72.0	75.2
20,000	28,600	65.3	67.3	71.0	72.4	76.0	80.5	83.4	85.7	87.8	91.1
22,000	31,400	78.8	80.8	85.2	86.8	91.0	96.3	99.8	102	105	109
24,000	34,300	93.4	96.0	101	103	107	113	118	121	124	128
26,000	37,100	109	112	117	120	124	132	137	140	143	148
28,000	40,000	126	129	135	138	143	152	157	161	165	170
30,000	42,850	145	148	155	158	163	173	179	184	188	194
32,000	45,700	164	168	176	179	185	196	203	208	212	219
34,000	48,600	184	189	197	201	207	220	227	233	238	246
36,000	51,400	206	211	219	224	231	245	253	260	266	374
38,000	54,300	229	235	244	249	257	272	281	288	294	303
40,000	57,150	252	260	269	274	283	299	309	317	324	333
42,000	60,000	277	286	296	301	312	328	339	347	355	365
44,000	62,900	303	313	323	329	341	357	370	380	388	399
46,000	65,700	330	342	352	359	372	388	402	413	422	435
48,000	68,600	358	371	382	389	403	421	436	447	456	471
50,000	71,450	387	401	413	420	435	455	471	483	492	509
55,000	78,600	470	486	500	507	524	546	565	580	591	609

TABLE F-15.—FRICTION LOSSES IN PIPE; 20 IN. (19.182 IN. ID); LOSS IN FEET OF LIQUID PER 1,000 FT OF PIPE (*Continued*)

Flow		Kinematic viscosity, centistokes									
		26.4	32.0	43.2	65.0	108.4	162.3	216.5	325	435	650
U.S. gpm	Bbl/hr (42 gal)	Approx. SSU viscosity									
		125	150	200	300	500	750	1,000	1,500	2,000	3,000
800	1,140	0.30	0.31	0.34	0.24	0.41	0.61	0.81	1.21	1.62	2.42
900	1,285	0.37	0.38	0.42	0.46	0.46	0.68	0.91	1.37	1.83	2.73
1,000	1,430	0.44	0.46	0.50	0.55	0.51	0.76	1.01	1.52	2.03	3.03
1,500	2,140	0.91	0.95	1.02	1.12	1.27	1.14	1.52	2.28	3.05	4.55
2,000	2,860	1.50	1.57	1.69	1.87	2.11	1.52	2.02	3.03	4.06	6.06
3,000	4,285	3.10	3.23	3.45	3.80	4.31	4.74	5.06	4.55	6.10	9.10
4,000	5,715	5.19	5.40	5.75	6.36	7.12	7.85	8.44	6.07	8.12	12.1
5,000	7,145	7.66	8.10	8.61	9.40	10.5	11.7	12.5	13.7	10.1	15.2
6,000	8,670	10.5	11.1	11.9	13.0	14.6	16.0	17.2	19.0	20.3	18.2
7,000	10,000	13.9	14.5	15.7	17.1	19.2	21.1	22.6	24.9	26.5	21.2
8,000	11,400	17.6	18.4	19.9	21.8	24.2	26.7	28.5	31.4	33.7	24.2
9,000	12,850	21.8	22.7	24.6	26.9	29.8	32.9	35.1	38.8	41.5	45.6
10,000	14,300	26.4	27.4	29.2	32.5	36.1	39.8	42.2	46.6	49.9	55.0
11,000	15,700	31.3	32.7	34.8	38.5	42.9	47.0	50.1	55.1	59.1	64.9
12,000	17,150	36.8	38.2	40.7	44.7	50.0	54.5	58.4	64.1	69.0	76.0
13,000	18,550	42.8	44.2	46.7	51.1	57.6	63.1	67.2	73.7	79.4	87.0
14,000	20,000	49.0	50.7	53.5	58.4	65.9	71.5	76.8	84.3	90.3	99.1
15,000	21,400	55.5	57.5	60.6	65.8	74.5	81.0	86.4	95.0	102	112
16,000	22,850	62.6	64.7	68.1	73.7	83.7	90.8	97.0	106	115	126
18,000	25,700	77.8	80.4	84.4	91.5	104	112	119	131	141	155
20,000	28,600	94.6	97.7	102	110	125	137	145	158	169	186
22,000	31,400	113	116	121	131	146	162	172	188	200	220
24,000	34,300	132	137	143	153	171	188	200	218	233	257
26,000	37,100	153	159	166	177	196	217	230	252	269	295
28,000	40,000	175	181	190	203	224	247	263	286	308	336
30,000	42,850	200	206	216	230	254	280	298	324	347	380
32,000	45,700	226	232	243	259	284	312	334	363	388	427
34,000	48,600	252	260	272	289	317	347	374	406	432	475
36,000	51,400	280	289	302	322	353	384	414	450	478	525
38,000	54,300	311	319	333	356	389	421	455	497	526	579
40,000	57,150	342	351	366	392	427	460	498	544	576	633
42,000	60,000	375	385	401	430	466	502	541	692	630	689
44,000	62,900	409	420	437	469	506	546	585	645	687	750
47,000	67,100	464	476	495	530	571	615	657	727	773	841
50,000	71,450	521	534	555	593	640	690	731	811	863	938

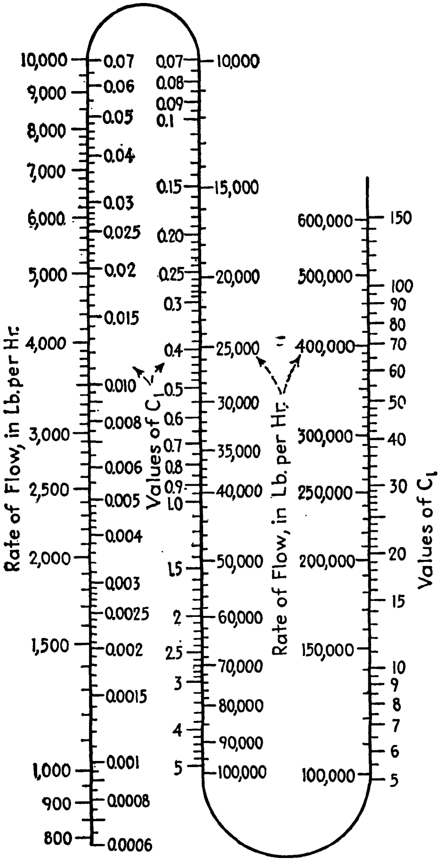

FIG. F-16.—Discharge factors (C_1) for use in Eq. (F-12). (*Reprinted from Technical Paper No. 409, Crane Co., Chicago, Ill., by permission.*)

Pressure drops in steam piping may readily be obtained by a method developed by the Crane Co.

$$\Delta p = C_1 C_2 C_3 V \tag{F-12}$$

where Δp = pressure drop, psi per 100 ft of pipe
V = specific volume of steam (see steam Tables E-13 to E-15)
C_1 = discharge factor from Fig. F-16
C_2 = size factor from Table F-16
C_3 = viscosity factor (Fig. F-17)

TABLE F-16.—SIZE FACTORS (C_2) FOR USE IN EQ. (F-12)
(Reprinted from *Tech. Paper* 409, Crane Co., Chicago, Ill., by permission)

Nominal pipe size	Schedule No.	Internal diameter	Value of C_2
1	40	1.049	6,420
	80	0.957	10,050
	160	0.815	21,950
1¼	40	1.380	1,687
	80	1.278	2,455
	160	1.160	3,935
1½	40	1.610	755
	80	1.500	1,067
	160	1.338	1,860
2	40	2.067	213
	80	1.939	291
	160	1.689	570
2½	40	2.469	80.1
	80	2.323	121
	160	2.125	188
3	40	3.068	31.2
	80	2.900	40.9
	160	2.626	66.7
3½	40	3.548	15.0
	80	3.364	19.5
4	40	4.026	7.73
	80	3.826	9.91
	120	3.626	12.8
	160	3.438	17.5
5	40	5.047	2.57
	80	4.813	3.18
	120	4.563	4.22
	160	4.313	5.52
6	40	6.065	1.00
	80	5.761	1.28
	120	5.501	1.62
	160	5.189	2.16
8	30	8.071	0.249
	40	7.981	0.263
	60	7.813	0.291
	80	7.625	0.328
	100	7.439	0.369
	120	7.189	0.435
	160	6.813	0.568
10	30	10.136	0.0819
	40	10.020	0.0866
	60	9.750	0.0980
	80	9.564	0.109
	100	9.314	0.1235
	120	9.064	0.141
	140	8.750	0.168
	160	8.500	0.193
12	30	12.090	0.0344
	40	11.938	0.0366
	60	11.626	0.0420
	80	11.376	0.0467
	100	11.064	0.0534
	120	10.750	0.0615
	140	10.500	0.0690
	160	10.126	0.0823

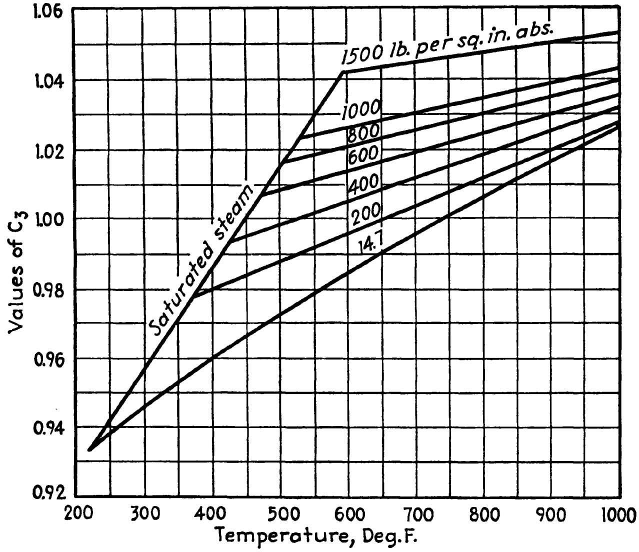

FIG. F-17.—Viscosity factors (C_3) for use in Eq. (F-12). (*Reprinted from Technical Paper No. 409, Crane Co., Chicago, Ill., by permission.*)

Pressure drops for flow of gases through steel pipes may be conveniently made by either the Spitzglass or the Weymouth formulas. Spitzglass formula for low-pressure gas, at 1 psig or less:

$$M = 3550\sqrt{\frac{h_w d^5}{SL(1 + 3.6/d + 0.03d)}} \tag{F-13}$$

where M = SCF/hr
h_w = pressure drop, measured as waterhead, in./ft
S = specific gravity relative to air
$= \frac{\text{molecular weight}}{28.9}$
L = length of pipe, ft
d = inside diameter of pipe, in.

Weymouth formula for high-pressure gas:

$$M = 28.0d^{2.667}\sqrt{\frac{p_1^2 - p_2^2}{SL_m}\frac{520}{T}} \tag{F-14}$$

where M = SCF/hr
d = inside pipe, diameter in.
S = specific gravity relative to air
L_m = length of pipe, miles
p_1 = initial pressure, psia
p_2 = final pressure, psia
T = absolute temperature, °R

4. Pressure Drops in Valves and Fittings

Like pressure drops through orifices and nozzles, much of the pressure drop through valves and fittings is due to velocity changes. Friction is more important, but equations of form similar to those used in orifice calculations are applicable. The usual form is

$$h = K\frac{u^2}{2g} \tag{F-15}$$

where h = pressure loss in head fluid, ft
K = experimental coefficient
u = average velocity in pipe leading to valve (or fitting), fps
g = 32.17, acceleration due to gravity, ft/sec^2

Values of the experimental coefficients are given in Table F-17. These coefficients are reasonably accurate, provided the flow is turbulent.

The "equivalent" length method, though less accurate than the foregoing, is much more convenient and is widely used. In this

TABLE F-17.—REPRESENTATIVE "K" VALUES FOR VARIOUS VALVES AND FITTINGS
K is experimental coefficient for use in Eq. (F-15)
(Reprinted from *Tech. Paper* 409, Crane Co., Chicago, Ill., by permission)

Type	K	Authority
Globe valve	10.0	Crane tests
Angle valve	5.0	Crane tests
Swing check valve (fully open)	2.5	Crane tests
Close return bend	2.2	
Standard tee	1.8	Giesecke & Badgett
Standard elbow	0.9	Giesecke & Badgett Crane tests
Medium-sweep elbow	0.75	
Long-sweep elbow	0.60	*Univ. Texas Bull.* 2712
45-deg elbow	0.42	*Univ. Texas Bull.* 2712
Gate valve (fully open)	0.19	*Univ. Wisconsin Bull.* 252
¼ closed	1.15	*Univ. Wisconsin Bull.* 252
½ closed	5.6	*Univ. Wisconsin Bull.* 252
¾ closed	24.0	*Univ. Wisconsin Bull.* 252
Borda entrance	0.83	Daugherty, "Hydraulics"
Sudden enlargement:		
$d_1/d_2 = 1/4$	0.92	Daugherty, "Hydraulics"
$d_1/d_2 = 1/2$	0.56	Daugherty, "Hydraulics"
$d_1/d_2 = 3/4$	0.19	Daugherty, "Hydraulics"
Ordinary entrance	0.5	Daugherty, "Hydraulics"
Sudden contraction:		
$d_2/d_1 = 1/4$	0.42	Daugherty, "Hydraulics"
$d_2/d_1 = 1/2$	0.33	Daugherty, "Hydraulics"
$d_2/d_1 = 3/4$	0.19	Daugherty, "Hydraulics"

method, the valve or fitting is said to be equivalent to so many feet or so many "pipe diameters" of pipe. This length is added to the

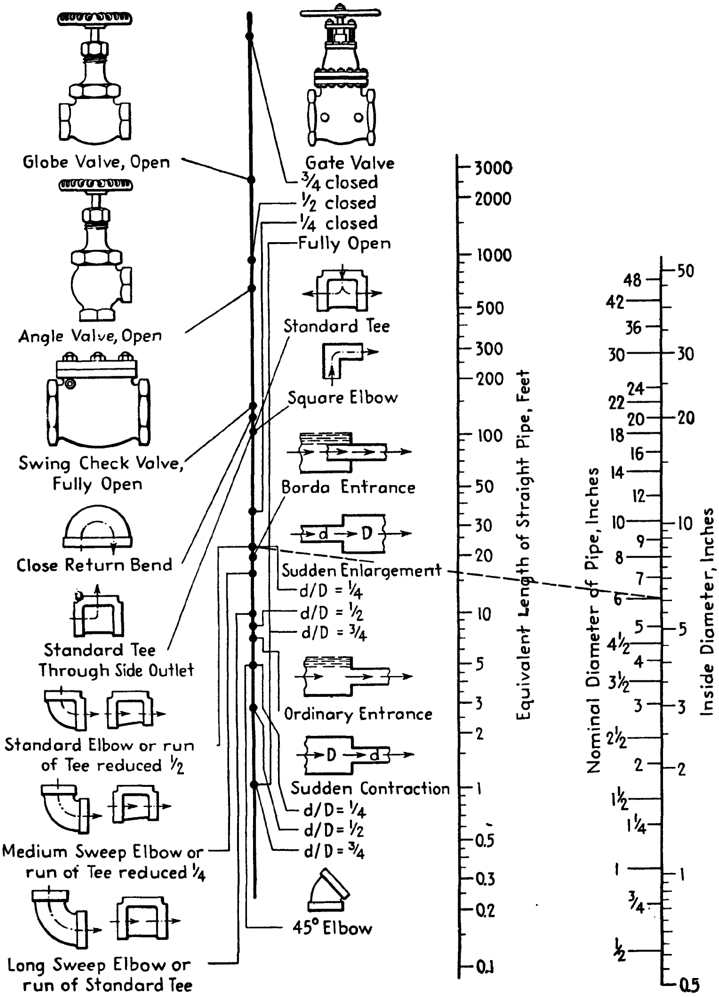

FIG. F-18.—Resistance of valves and fittings to flow of fluids. (*Reprinted from Technical Paper No. 409, Crane Co., Chicago, Ill., by permission.*)

pipe length, and the entire pressure drop is computed at once. Figure F-18 gives such equivalent lengths.

5. Pipe and Fitting Data

The exposed areas (and pipe lengths of same areas) for valves and fittings are given in Table F-18. Data on steel and iron pipe sizes are given in Table F-19 and similar data for condenser tubes in Table F-20.

Table F-18.—Total Radiating Area of Flanged Fittings
(Including accompanying flanges)
(Reprinted from "Heat Insulation Handbook," Ehret Magnesia Manufacturing Co., Valley Forge, Pa., by permission)
In square feet and in equivalent length of same size pipe

Standard weight fittings

Pipe size, in.	Flanged couplings		90-deg ells		Long-radius ells		Tees		Crosses	
	Area, sq ft	Pipe length, ft	Area, sq ft	Pipe length, ft	Area, sq ft	Pipe length, ft	Area, sq ft	Pipe length, ft	Area, sq ft	Pipe length, ft
1	0.32	0.93	0.79	2.31	0.89	2.59	1.24	3.59	1.62	4.72
1¼	0.38	0.88	0.96	2.20	1.08	2.49	1.48	3.40	1.94	4.47
1½	0.48	0.95	1.17	2.35	1.34	2.68	1.82	3.64	2.38	4.78
2	0.67	1.08	1.65	2.65	1.84	2.96	2.54	4.08	3.32	5.34
2½	0.84	1.12	2.09	2.78	2.32	3.08	3.21	4.26	4.19	5.56
3	0.95	1.03	2.38	2.60	2.68	2.93	3.66	3.99	4.77	5.70
3½	1.12	1.07	2.98	2.85	3.28	3.13	4.48	4.28	5.83	5.56
4	1.34	1.14	3.53	2.90	3.96	3.36	5.41	4.59	7.03	5.97
4½	1.47	1.13	3.95	3.01	4.43	3.38	6.07	4.63	7.87	6.01
5	1.62	1.11	4.44	3.05	5.00	3.43	6.81	4.67	8.82	6.06
6	1.82	1.05	5.13	2.95	5.99	3.45	7.84	4.53	10.08	5.81
7	2.17	1.05	6.17	3.09	7.38	3.70	9.37	4.69	12.00	6.01
8	2.41	1.07	6.98	3.09	8.56	3.79	10.55	4.67	13.44	5.96
9	3.00	1.19	8.71	3.46	10.57	4.20	13.18	5.23	16.78	6.66
10	3.43	1.22	10.18	3.61	12.35	4.38	15.41	5.47	19.58	6.95
12	4.41	1.32	13.08	3.92	16.35	4.90	19.67	5.89	24.87	7.45
14	5.39	1.47	16.38	4.47	20.17	5.47	24.81	6.78	31.48	8.60
16	6.69	1.60	20.17	4.82	25.41	6.07	30.32	7.23	38.34	9.15

TABLE F-19.—STEEL-PIPE DIMENSIONS, CAPACITIES, AND WEIGHTS*
(Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York, 1941)

Nominal pipe size, in.	Outside diam., in.	Schedule No.	Wall thickness, in.	Inside diam., in.	Cross-sectional area metal, sq in.	Inside sectional area, sq ft	Circumference, ft, or surface, sq ft/ft, of length		Capacity at 1 ft/sec velocity		Weight of pipe per ft, lb
							Outside	Inside	U.S. gpm	Lb/hr water	
⅛	0.405	40†	0.068	0.269	0.072	0.00040	0.106	0.0705	0.179	89.5	0.25
		80‡	0.095	0.215	0.093	0.00025	0.106	0.0563	0.112	56.0	0.32
¼	0.540	40†	0.088	0.364	0.125	0.00072	0.141	0.0954	0.323	161.5	0.43
		80‡	0.119	0.302	0.157	0.00050	0.141	0.0792	0.224	112.0	0.54
⅜	0.675	40†	0.091	0.493	0.167	0.00133	0.177	0.1293	0.596	298.0	0.57
		80‡	0.126	0.423	0.217	0.00098	0.177	0.1110	0.440	220.0	0.74
½	0.840	40†	0.109	0.622	0.250	0.00211	0.220	0.1630	0.945	472.5	0.85
		80‡	0.147	0.546	0.320	0.00163	0.220	0.1430	0.730	365.0	1.09
		160	0.187	0.466	0.384	0.00118	0.220	0.1220	0.529	264.5	1.31
¾	1.050	40†	0.113	0.824	0.333	0.00371	0.275	0.2158	1.665	832.5	1.13
		80‡	0.154	0.742	0.433	0.00300	0.275	0.1942	1.345	672.5	1.48
		160	0.218	0.614	0.570	0.00206	0.275	0.1610	0.924	462.0	1.94
1	1.315	40†	0.133	1.049	0.494	0.00600	0.344	0.2745	2.690	1,345.0	1.68
		80‡	0.179	0.957	0.639	0.00499	0.344	0.2505	2.240	1,120.0	2.17
		160	0.250	0.815	0.837	0.00362	0.344	0.2135	1.625	812.5	2.85

1¼	1.660	40†	0.140	1.380	0.669	0.01040	0.435	0.362	4.57	2,285.0	2.28
		80‡	0.191	1.278	0.881	0.00891	0.435	0.335	3.99	1,995.0	3.00
		160	0.250	1.160	1.107	0.00734	0.435	0.304	3.29	1,645.0	3.77
1½	1.900	40†	0.145	1.610	0.799	0.01414	0.498	0.422	6.34	3,170.0	2.72
		80‡	0.200	1.500	1.068	0.01225	0.498	0.393	5.49	2,745.0	3.64
		160	0.281	1.338	1.429	0.00976	0.498	0.350	4.38	2,190.0	4.86
2	2.375	40†	0.154	2.067	1.075	0.02330	0.622	0.542	10.45	5,225.0	3.66
		80‡	0.218	1.939	1.477	0.02050	0.622	0.508	9.20	4,600.0	5.03
		160	0.343	1.689	2.190	0.01556	0.622	0.442	6.97	3,485.0	7.45
2½	2.875	40†	0.203	2.469	1.704	0.03322	0.753	0.647	14.92	7,460.0	5.80
		80‡	0.276	2.323	2.254	0.02942	0.753	0.609	13.20	6,600.0	7.67
		160	0.375	2.125	2.945	0.02463	0.753	0.557	11.07	5,535.0	10.0
3	3.500	40†	0.216	3.068	2.228	0.05130	0.917	0.804	23.00	11,500.0	7.58
		80‡	0.300	2.900	3.016	0.04587	0.917	0.760	20.55	10,275.0	10.3
		160	0.437	2.626	4.205	0.03761	0.917	0.688	16.90	8,450.0	14.3
3½	4.000	40†	0.226	3.548	2.680	0.06870	1.047	0.930	30.80	15,400.0	9.11
		80‡	0.318	3.364	3.678	0.06170	1.047	0.882	27.70	13,850.0	12.5
4	4.500	40†	0.237	4.026	3.173	0.08840	1.178	1.055	39.6	19,800.0	10.8
		80‡	0.337	3.826	4.407	0.07986	1.178	1.002	35.8	17,900.0	15.0
		120	0.437	3.626	5.578	0.07170	1.178	0.950	32.2	16,100.0	19.0
		160	0.531	3.438	6.621	0.06447	1.178	0.901	28.9	14,450.0	22.6

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* Based on A.S.A. Standards B36.10.

† Designates former "standard" sizes.

‡ Former "extra strong."

TABLE F-19.—STEEL-PIPE DIMENSIONS, CAPACITIES, AND WEIGHTS* (*Continued*)

Nominal pipe size, in.	Outside diam., in.	Schedule No.	Wall thick-ness, in.	Inside diam., in.	Cross-sectional area metal, sq in.	Inside sectional area, sq ft	Circumference, ft, or surface, sq ft/ft, of length		Capacity at 1 ft/sec velocity		Weight of pipe per ft, lb
							Outside	Inside	U.S. gpm	Lb/hr water	
5	5.563	40†	0.258	5.047	4.304	0.1390	1.456	1.322	62.3	31,150.0	14.7
		80‡	0.375	4.813	6.112	0.1263	1.456	1.263	57.7	28,850.0	20.8
		120	0.500	4.563	7.953	0.1136	1.456	1.197	51.0	25,500.0	27.1
		160	0.625	4.313	9.696	0.1015	1.456	1.132	45.5	22,750.0	33.0
6	6.625	40†	0.280	6.065	5.584	0.2006	1.734	1.590	90.0	45,000.0	19.0
		80‡	0.432	5.761	8.405	0.1810	1.734	1.510	81.1	40,550.0	28.6
		120	0.562	5.501	10.71	0.1650	1.734	1.445	73.9	36,950.0	36.4
		160	0.718	5.189	13.32	0.1469	1.734	1.360	65.8	32,900.0	45.3
8	8.625	20	0.250	8.125	6.570	0.3601	2.258	2.130	161.5	80,750.0	22.4
		30†	0.277	8.071	7.260	0.3553	2.258	2.115	159.4	79,700.0	24.7
		40†	0.322	7.981	8.396	0.3474	2.258	2.090	155.7	77,850.0	28.6
		60	0.406	7.813	10.48	0.3329	2.258	2.050	149.4	74,700.0	35.7
		80‡	0.500	7.625	12.76	0.3171	2.258	2.000	142.3	71,150.0	43.4
		100	0.593	7.439	14.96	0.3018	2.258	1.947	135.3	67,650.0	50.9
		120	0.718	7.189	17.84	0.2819	2.258	1.883	126.5	63,250.0	60.7
		140	0.812	7.001	19.93	0.2673	2.258	1.835	120.0	60,000.0	67.8
		160	0.906	6.813	21.97	0.2532	2.258	1.787	113.5	56,750.0	74.7
10	10.75	20	0.250	10.250	8.24	0.5731	2.814	2.685	257.0	128,500.0	28.1
		30†	0.307	10.136	10.07	0.5603	2.814	2.655	252.0	126,000.0	34.3
		40†	0.365	10.020	11.90	0.5475	2.814	2.620	246.0	123,000.0	40.5

		60‡	0.500	9.750	16.10	0.5185	2.814	2.550	233.0	116,500.0	54.8
		80	0.593	9.564	18.92	0.4989	2.814	2.503	224.0	112,000.0	64.4
		100	0.718	9.314	22.63	0.4732	2.814	2.440	212.0	106,000.0	77.0
		120	0.843	9.064	26.24	0.4481	2.814	2.373	201.0	100,500.0	89.2
		140	1.000	8.750	30.63	0.4176	2.814	2.290	188.0	93,750.0	105.0
		160	1.125	8.500	34.02	0.3941	2.814	2.230	177.0	88,500.0	116.0
12	12.75	20	0.250	12.250	9.82	0.8185	3.338	3.21	367.0	183,500.0	33.4
		30†	0.330	12.090	12.87	0.7972	3.338	3.17	358.0	179,000.0	43.8
		40	0.406	11.938	15.77	0.7773	3.338	3.13	349.0	174,500.0	53.6
		60	0.562	11.626	21.52	0.7372	3.338	3.05	331.0	165,500.0	73.2
		80	0.687	11.376	26.03	0.7058	3.338	2.98	317.0	158,500.0	88.6
		100	0.843	11.064	31.53	0.6677	3.338	2.90	299.0	149,500.0	108.0
		120	1.000	10.750	36.91	0.6303	3.338	2.82	283.0	141,500.0	126.0
		140	1.125	10.500	41.08	0.6013	3.338	2.75	270.0	135,000.0	140.0
		160	1.312	10.126	47.14	0.5592	3.338	2.66	251.0	125,500.0	161.0
14	14.0	10	0.250	13.500	10.80	0.9940	3.665	3.54	446.0	223,000.0	36.8
		20	0.312	13.376	13.42	0.9750	3.665	3.51	438.0	219,000.0	45.7
		30	0.375	13.250	16.05	0.9575	3.665	3.47	430.0	215,000.00	54.6
		40	0.437	13.126	18.61	0.9397	3.665	3.44	422.0	211,000.0	63.3
		60	0.593	12.814	24.98	0.8956	3.665	3.36	402.0	201,000.0	85.0
		80	0.750	12.500	31.22	0.8522	3.665	3.28	382.0	191,000.0	107.0
		100	0.937	12.126	38.45	0.8020	3.665	3.18	360.0	180,000.0	131.0
		120	1.062	11.876	43.17	0.7693	3.665	3.11	345.0	172,500.0	147.0
		140	1.250	11.500	50.07	0.7213	3.665	3.01	324.0	162,000.0	171.0
		160	1.406	11.188	55.63	0.6827	3.665	2.93	306.0	153,000.0	190.0

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* Based on A.S.A. Standards B36.10.

† Designates former "standard" sizes.

‡ Former "extra strong."

TABLE F-19.—STEEL-PIPE DIMENSIONS, CAPACITIES, AND WEIGHTS* (*Concluded*)

Nominal pipe size, in.	Outside diam., in.	Schedule No.	Wall thickness, in.	Inside diam., in.	Cross-sectional area metal, sq in.	Inside sectional area, sq ft	Circumference, ft, or surface, sq ft/ft, of length		Capacity at 1 ft/sec velocity		Weight of pipe per ft, lb
							Outside	Inside	U.S. gpm	Lb/hr water	
16	16.0	10	0.250	15.500	12.37	1.3104	4.189	4.06	587.0	293,500.0	42.1
		20	0.312	15.376	15.38	1.2895	4.189	4.03	578.0	289,000.0	52.3
		30	0.375	15.250	18.41	1.2680	4.189	4.00	568.0	284,000.0	62.6
		40	0.500	15.000	24.35	1.2272	4.189	3.93	550.0	275,000.0	82.8
		60	0.656	14.688	31.62	1.1766	4.189	3.85	528.0	264,000.0	108.0
		80	0.843	14.314	40.14	1.1175	4.189	3.76	500.0	250,000.0	137.0
		100	1.031	13.938	48.48	1.0596	4.189	3.65	474.0	237,000.0	165.0
		120	1.218	13.564	56.56	1.0035	4.189	3.56	450.0	225,000.0	193.0
		140	1.437	13.126	65.74	0.9397	4.189	3.44	422.0	211,000.0	224.0
		160	1.562	12.876	70.85	0.9043	4.189	3.37	405.0	202,500.0	241.0
18	18.0	10	0.250	17.50	13.94	1.6703	4.712	4.59	748.0	374,000.0	47.4
		20	0.312	17.376	17.34	1.6468	4.712	4.55	738.0	369,000.0	59.0
		30	0.437	17.126	24.11	1.5993	4.712	4.49	717.0	358,500.0	82.0
		40	0.562	16.876	30.79	1.5533	4.712	4.42	697.0	348,500.0	105.0
		60	0.718	16.564	38.98	1.4964	4.712	4.34	670.0	335,000.0	133.0
		80	0.937	16.126	50.23	1.4183	4.712	4.23	635.0	317,500.0	171.0
		100	1.156	15.688	61.17	1.3423	4.712	4.11	602.0	301,000.0	208.0
		120	1.343	15.314	70.28	1.2791	4.712	4.02	573.0	286,500.0	239.0
		140	1.562	14.876	80.66	1.2070	4.712	3.90	540.0	270,000.0	275.0
		160	1.750	14.500	89.34	1.1467	4.712	3.80	514.0	257,000.0	304.0

20	20.0	10	0.250	19.500	15.51	2.0740	5.236	5.11	930.0	465,000.0	52.8
		20	0.375	19.250	23.12	2.0211	5.236	5.05	902.0	451,000.0	78.6
		30	0.500	19.000	30.63	1.9689	5.236	4.98	883.0	441,500.0	105.0
		40	0.593	18.814	36.15	1.9305	5.236	4.94	866.0	433,000.0	123.0
		60	0.812	18.376	48.95	1.8417	5.236	4.81	826.0	413,000.0	167.0
		80	1.031	17.938	61.44	1.7550	5.236	4.70	787.0	393,500.0	209.0
		100	1.250	17.500	73.63	1.6703	5.236	4.59	750.0	375,000.0	251.0
		120	1.500	17.000	87.18	1.5762	5.236	4.46	707.0	353,500.0	297.0
		140	1.750	16.500	100.3	1.4849	5.236	4.32	665.0	332,500.0	342.0
		160	1.937	16.126	109.9	1.4183	5.236	4.22	635.0	317,500.0	374.0
24	24.0	10	0.250	23.500	18.65	3.012	6.283	6.16	1,350.0	675,000.0	63.5
		20	0.375	23.250	27.83	2.948	6.283	6.09	1,325.0	662,500.0	94.7
		30	0.562	22.876	41.39	2.854	6.283	6.00	2,380.0	640,000.0	141.0
		40	0.687	22.626	50.31	2.792	6.283	5.94	1,254.0	627,000.0	171.0
		60	0.937	22.126	67.89	2.670	6.283	5.80	1,200.0	600,000.0	231.0
		80	1.218	21.564	87.17	2.536	6.283	5.65	1,136.0	568,000.0	297.0
		100	1.500	21.000	106.0	2.405	6.283	5.50	1,080.0	540,000.0	361.0
		120	1.750	20.500	122.3	2.292	6.283	5.37	1,030.0	515,000.0	416.0
		140	2.062	19.876	142.1	2.155	6.283	5.21	965.0	482,500.0	484.0
		160	2.312	19.376	157.5	2.048	6.283	5.08	918.0	409,000.0	536.0
30	30.0	10	0.312	29.376	29.10	4.707	7.854	7.69	2,110.0	1,055,000.0	99.0
		20	0.500	29.000	46.34	4.587	7.854	7.60	2,055.0	1,027,500.0	158.0
		30	0.625	28.750	57.68	4.508	7.854	7.53	2,020.0	1,010,000.0	197.0

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* Based on A.S.A. Standards B36.10.

† Designates former "standard" sizes.

‡ Former "extra strong."

TABLE F-20.—CONDENSER AND HEAT-EXCHANGER TUBE DIMENSIONS (Perry, "Chemical Engineers' Handbook, 2d ed., McGraw-Hill Book Company, Inc., New York, 1941)

Outside diam., in.	Wall thickness		Inside diam., in.	Cross-sectional area metal, sq in.	Inside sectional area, sq ft	Circumference, ft, or surface, sq ft/ft of length		Velocity, fps for 1 U.S. gpm	Capacity at 1 fps velocity		Weight per ft, lb†
	B.W.G. and Stubs' gauge*	In.				Outside	Inside		U.S. gpm	Lb/hr water	
¼	14	0.083	0.084	0.0435	0.000039	0.0654	0.0219	57.14	0.0175	8.75	0.161
	16	0.065	0.120	0.0377	0.000079	0.0654	0.0314	28.20	0.0355	17.73	0.140
	18	0.049	0.152	0.0309	0.000126	0.0654	0.0397	17.68	0.0566	28.30	0.115
	20	0.035	0.180	0.0236	0.000177	0.0654	0.0471	12.59	0.0794	39.70	0.0876
	22	0.028	0.194	0.0195	0.000205	0.0654	0.0507	10.869	0.0920	46.00	0.0724
	24	0.022	0.206	0.0157	0.000231	0.0654	0.0539	9.645	0.1037	51.85	0.0584
⅜	14	0.083	0.209	0.0761	0.000238	0.0981	0.0547	9.362	0.1068	53.40	0.282
	16	0.065	0.245	0.0633	0.000327	0.0981	0.0641	6.814	0.1468	73.40	0.235
	18	0.049	0.277	0.0501	0.000418	0.0981	0.0725	5.330	0.1876	93.80	0.186
	20	0.035	0.305	0.0373	0.000507	0.0981	0.0798	4.395	0.2275	113.8	0.139
	22	0.028	0.319	0.0305	0.000555	0.0981	0.0835	4.015	0.2494	124.7	0.113
	24	0.022	0.331	0.0243	0.000597	0.0981	0.0866	3.732	0.2679	134.0	0.0904
½	12	0.109	0.282	0.1338	0.000433	0.1309	0.0748	5.142	0.1945	97.25	0.493
	14	0.083	0.334	0.1087	0.000608	0.1309	0.0874	3.662	0.2730	136.5	0.403
	16	0.065	0.370	0.0888	0.000747	0.1309	0.0969	2.981	0.3352	167.5	0.329
	18	0.049	0.402	0.0694	0.000882	0.1309	0.1052	2.530	0.3952	197.6	0.258
	20	0.035	0.430	0.0511	0.001009	0.1309	0.1125	2.209	0.4528	226.4	0.190
⅝	10	0.134	0.357	0.2067	0.000695	0.1636	0.0935	3.206	0.3119	156.0	0.769
	11	0.120	0.385	0.1904	0.000808	0.1636	0.1008	2.758	0.3626	181.3	0.708
	12	0.109	0.407	0.1767	0.000903	0.1636	0.1066	2.468	0.4053	202.7	0.657
	13	0.095	0.435	0.1582	0.00103	0.1636	0.1139	2.163	0.4623	231.2	0.588
	14	0.083	0.459	0.1460	0.00115	0.1636	0.1202	1.938	0.5161	258.1	0.526
	15	0.072	0.481	0.1250	0.00126	0.1636	0.1259	1.768	0.5655	258.9	0.465
	16	0.065	0.495	0.1143	0.00134	0.1636	0.1296	1.663	0.6014	300.7	0.425
	17	0.058	0.509	0.1033	0.00141	0.1636	0.1333	1.580	0.6328	316.4	0.384
	18	0.049	0.527	0.0887	0.00151	0.1636	0.1380	1.476	0.6777	338.9	0.330
	19	0.042	0.561	0.0596	0.00160	0.1636	0.1469	1.393	0.7181	359.1	0.286
¾	10	0.134	0.482	0.2593	0.00127	0.1963	0.1262	1.754	0.5700	235.0	0.965
	11	0.120	0.510	0.2375	0.00142	0.1963	0.1335	1.569	0.6373	318.7	0.884
	12	0.109	0.532	0.2195	0.00154	0.1963	0.1393	1.447	0.6912	345.6	0.817
	13	0.095	0.560	0.1955	0.00171	0.1963	0.1466	1.303	0.7674	383.7	0.727
	14	0.083	0.584	0.1739	0.00186	0.1963	0.1529	1.198	0.8348	417.4	0.647
	15	0.072	0.606	0.1534	0.00200	0.1963	0.1587	1.114	0.8976	448.8	0.571
	16	0.065	0.620	0.1398	0.00210	0.1963	0.1623	1.061	0.9425	471.3	0.520
	17	0.058	0.634	0.1261	0.00219	0.1963	0.1660	1.017	0.9829	491.5	0.469
	18	0.049	0.652	0.1079	0.00232	0.1963	0.1707	0.962	1.041	520.5	0.401
	19	0.042	0.666	0.0934	0.00242	0.1963	0.1744	0.920	1.086	543.0	0.348
⅞	9	0.148	0.579	0.3380	0.00183	0.2291	0.1516	1.218	0.8213	410.7	1.26
	10	0.134	0.607	0.3119	0.00201	0.2291	0.1589	1.109	0.9021	451.1	1.16

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* B.W.G. = Birmingham wire gauge, commonly used for ferrous tubing; it is identical with Stubs' = Stubs' iron-wire gauge.

† In brass, sp gr = 8.56; sp gr of steel = 7.8.

TABLE F-20.—CONDENSER AND HEAT-EXCHANGER TUBE DIMENSIONS (*Continued*)

Outside diam., in.	Wall thickness		Inside diam., in.	Cross-sectional area metal, sq in.	Inside sectional area, sq ft	Circumference, ft, or surface, sq ft/ft of length		Velocity, fps for 1 U.S. gpm	Capacity at 1 fps velocity		Weight per ft, lb†
	B.W.G. and Stubs' gauge*	In.				Outside	Inside		U.S. gpm	Lb/hr water	
⅞	11	0.120	0.635	0.2846	0.00220	0.2291	0.1662	1.012	0.9874	493.7	1.06
	12	0.109	0.657	0.2623	0.00235	0.2291	0.1720	0.948	1.055	527.5	0.976
	13	0.095	0.685	0.2328	0.00256	0.2291	0.1793	0.870	1.149	574.5	0.866
	14	0.083	0.709	0.2065	0.00274	0.2291	0.1856	0.813	1.230	615.0	0.768
	15	0.072	0.731	0.1816	0.00291	0.2291	0.1914	0.766	1.306	653.0	0.676
	16	0.065	0.745	0.1654	0.00303	0.2291	0.1950	0.735	1.360	680.0	0.615
	17	0.058	0.759	0.1488	0.00314	0.2291	0.1987	0.709	1.409	704.5	0.554
	18	0.049	0.777	0.1271	0.00329	0.2291	0.2034	0.678	1.477	738.5	0.473
	19	0.042	0.791	0.1099	0.00341	0.2291	0.2071	0.654	1.530	751.5	0.409
1	7	0.180	0.640	0.4637	0.00223	0.2618	0.1676	0.999	1.001	500.5	1.73
	8	0.165	0.670	0.4328	0.00245	0.2618	0.1754	0.909	1.100	505.0	1.61
	9	0.148	0.704	0.3962	0.00270	0.2618	0.1843	0.826	1.212	606.0	1.47
	10	0.134	0.732	0.3654	0.00292	0.2618	0.1916	0.763	1.310	655.0	1.36
	11	0.120	0.760	0.3318	0.00315	0.2618	0.1990	0.707	1.414	707.0	1.23
	12	0.109	0.782	0.3051	0.00334	0.2618	0.2048	0.667	1.499	750.0	1.14
	13	0.095	0.810	0.2701	0.00358	0.2618	0.2121	0.622	1.607	803.5	1.00
	14	0.083	0.834	0.2391	0.00379	0.2618	0.2183	0.588	1.701	850.5	0.890
	15	0.072	0.856	0.2099	0.00400	0.2618	0.2241	0.557	1.795	897.5	0.781
	16	0.065	0.870	0.1909	0.00413	0.2618	0.2277	0.538	1.854	927.0	0.710
	17	0.058	0.884	0.1716	0.00426	0.2618	0.2314	0.523	1.912	956.0	0.639
	18	0.049	0.902	0.1463	0.00444	0.2618	0.2361	0.501	1.993	996.5	0.545
	19	0.042	0.916	0.1264	0.00458	0.2618	0.2398	0.486	2.056	1028.0	0.470
1⅛	7	0.180	0.765	0.5355	0.00319	0.2945	0.2003	0.698	1.432	716.0	1.99
	8	0.165	0.795	0.4979	0.00345	0.2945	0.2081	0.646	1.548	774.0	1.85
	9	0.148	0.829	0.4546	0.00375	0.2945	0.2170	0.594	1.683	841.5	1.69
	10	0.134	0.857	0.4175	0.00401	0.2945	0.2244	0.556	1.800	900	1.55
	11	0.120	0.885	0.3792	0.00427	0.2945	0.2317	0.521	1.916	958	1.41
	12	0.109	0.907	0.3479	0.00449	0.2945	0.2375	0.496	2.015	1008	1.29
	13	0.095	0.935	0.3074	0.00477	0.2945	0.2448	0.467	2.141	1071	1.14
	14	0.083	0.959	0.2717	0.00502	0.2945	0.2511	0.443	2.253	1127	1.01
	15	0.072	0.981	0.2381	0.00525	0.2945	0.2568	0.424	2.356	1178	0.886
	16	0.065	0.995	0.2165	0.00540	0.2945	0.2605	0.412	2.424	1212	0.805
	17	0.058	1.009	0.1944	0.00555	0.2945	0.2642	0.401	2.491	1246	0.723
	18	0.049	1.029	0.1624	0.00575	0.2945	0.2694	0.387	2.581	1291	0.616
	19	0.042	1.041	0.1429	0.00591	0.2945	0.2725	0.377	2.652	1326	0.532
1¼	7	0.180	0.890	0.6051	0.00432	0.3271	0.2330	0.516	1.939	969.5	2.25
	8	0.165	0.920	0.5624	0.00462	0.3271	0.2409	0.482	2.073	1037	2.09
	9	0.148	0.954	0.5124	0.00496	0.3271	0.2498	0.449	2.226	1113	1.91
	10	0.134	0.982	0.4698	0.00526	0.3271	0.2572	0.424	2.361	1181	1.75
	11	0.120	1.010	0.4260	0.00556	0.3271	0.2644	0.401	2.495	1248	1.58
	12	0.109	1.032	0.3907	0.00581	0.3271	0.2701	0.384	2.608	1304	1.45
	13	0.095	1.060	0.3447	0.00613	0.3271	0.2775	0.363	2.751	1376	1.28

* B.W.G. = Birmingham wire gauge, commonly used for ferrous tubing; it is identical with Stubs' = Stubs' iron-wire gauge.

† In brass, sp gr = 8.56; sp gr of steel = 7.8.

TABLE F-20.—CONDENSER AND HEAT-EXCHANGER TUBE DIMENSIONS (*Continued*)

Outside diam., in.	Wall thickness		Inside diam., in.	Cross-sectional area metal, sq in.	Inside sectional area, sq ft	Circumference, ft, or surface, sq ft/ft of length		Velocity, fps for 1 U.S. gpm	Capacity at 1 fps velocity		Weight per ft, lb†
	B.W.G. and Stubs' gauge*	In.				Outside	Inside		U.S. gpm	Lb/hr water	
1¼	14	0.083	1.084	0.3042	0.00641	0.3271	0.2839	0.348	2.877	1439	1.13
	15	0.072	1.106	0.2665	0.00667	0.3271	0.2896	0.334	2.993	1497	0.991
	16	0.065	1.120	0.2419	0.00684	0.3271	0.2932	0.326	3.070	1535	0.900
	17	0.058	1.134	0.2172	0.00701	0.3271	0.2969	0.318	3.146	1573	0.808
	18	0.049	1.152	0.1848	0.00724	0.3271	0.3015	0.308	3.249	1625	0.688
	19	0.042	1.166	0.1590	0.00742	0.3271	0.3053	0.300	3.330	1665	0.593
1⅜	7	0.180	1.015	0.6758	0.00562	0.3620	0.2657	0.397	2.522	1261	2.51
	8	0.165	1.045	0.6272	0.00596	0.3620	0.2736	0.374	2 675	1338	2.33
	9	0.148	1.079	0.5705	0.00635	0.3620	0.2825	0.351	2.850	1425	2.12
	10	0.134	1.107	0.5224	0.00668	0.3620	0.2898	0.334	2.998	1499	1.94
	11	0.120	1.135	0.4731	0.00703	0.3620	0.2971	0.317	3.155	1578	1.76
	12	0.109	1.157	0.4335	0.00730	0.3620	0.3029	0.305	3.276	1638	1.61
	13	0.095	1.185	0.3820	0.00766	0.3620	0.3102	0.291	3.438	1719	1.42
	14	0.083	1.209	0.3369	0.00797	0.3620	0.3165	0.280	3.577	1789	1.25
	15	0.072	1.231	0.2947	0.00827	0.3620	0.3223	0.269	3.712	1856	1.10
	16	0.065	1.245	0.2675	0.00845	0.3620	0.3259	0.264	3.792	1896	0.995
	17	0.058	1.259	0.2399	0.00865	0.3620	0.3296	0.258	3.882	1941	0.893
	18	0.049	1.277	0.2041	0.00889	0.3620	0.3343	0.251	3.990	1995	0.759
	19	0.042	1.291	0.1759	0.00909	0.3620	0.3380	0.245	4.080	2040	0.654
1½	7	0.180	1.140	0.7464	0.00709	0.3925	0.2985	0.314	3.182	1591	2.78
	8	0.165	1.170	0.6920	0.00747	0.3925	0.3063	0.298	3.353	1677	2.57
	9	0.148	1.204	0.6286	0.00791	0.3925	0.3152	0.282	3.550	1775	2.34
	10	0.134	1.232	0.5750	0.00828	0.3925	0.3225	0.269	3.716	1858	2.14
	11	0.120	1.260	0.5202	0.00866	0.3925	0.3299	0.257	3 887	1944	1.94
	12	0.109	1.282	0.4763	0.00896	0.3925	0.3356	0.249	4.021	2011	1.77
	13	0.095	1.310	0.4193	0.00936	0.3925	0.3430	0.238	4.201	2101	1.56
	14	0.083	1.334	0.3694	0.00971	0.3925	0.3492	0.229	4.358	2176	1.37
	15	0.072	1.358	0.3187	0.0100	0.3925	0.3555	0.223	4.488	2244	1.20
	16	0.065	1.370	0.2930	0.0102	0.3925	0.3587	0.218	4.578	2289	1.09
	17	0.058	1.384	0.2627	0.0104	0.3925	0.3623	0.214	4.668	2334	0.978
	18	0.049	1.402	0.2234	0.0107	0.3925	0.3670	0.208	4.802	2401	0.831
	19	0.042	1.416	0.1923	0.0109	0.3925	0.3707	0.204	4.892	2446	0.716
1⅝	7	0.180	1.265	0.8171	0.00873	0.4254	0.3312	0.255	3.918	1959	3.04
	8	0.165	1.295	0.8354	0.00915	0.4254	0.3390	0.243	4.107	2054	2.82
	9	0.148	1.329	0.6868	0.00963	0.4254	0.3479	0.231	4.322	2161	2.55
	10	0.134	1.357	0.6198	0.0100	0.4254	0.3553	0.223	4.488	2244	2.34
	11	0.120	1.385	0.5674	0.0105	0.4254	0.3626	0.212	4.712	2356	2.11
	12	0.109	1.407	0.5191	0.0108	0.4254	0.3684	0.206	4.847	2424	1.93
	13	0.095	1.435	0.4566	0.0112	0.4254	0.3757	0.199	5.027	2514	1.70
	14	0.083	1.459	0.4020	0.0116	0.4254	0.3820	0.192	5.206	2603	1.50
	15	0.072	1.481	0.3512	0.0120	0.4254	0.3877	0.186	5.386	2693	1.31

* B.W.G. = Birmingham wire gauge, commonly used for ferrous tubing; it is identical with Stubs' = Stubs' iron-wire gauge.

† In brass, sp gr = 8.56; sp gr of steel = 7.8.

TABLE F-20.—CONDENSER AND HEAT-EXCHANGER TUBE DIMENSIONS (*Concluded*)

Outside diam., in.	Wall thickness		Inside diam., in.	Cross-sectional area metal, sq in.	Inside sectional area, sq ft	Circumference, ft, or surface, sq ft/ft of length		Velocity, fps for 1 U.S. gpm	Capacity at 1 fps velocity		Weight per ft, lb†
	B.W.G. and Stubs' gauge*	In.				Outside	Inside		U.S. gpm	Lb/hr water	
1⅝	16	0.065	1.495	0.3186	0.0122	0.4254	0.3914	0.183	5.475	2738	1.19
	17	0.058	1.509	0.2855	0.0124	0.4254	0.3951	0.180	5.565	2783	1.06
	18	0.049	1.527	0.2426	0.0127	0.4254	0.3998	0.175	5.700	2850	0.903
	19	0.042	1.541	0.2300	0.0130	0.4254	0.4034	0.171	5.834	2967	0.777
1¾	7	0.180	1.390	0.8878	0.0105	0.4582	0.3639	0.212	4.712	2356	3.30
	8	0.165	1.420	0.8216	0.0110	0.4582	0.3718	0.203	4.937	2469	3.06
	9	0.148	1.454	0.7449	0.0115	0.4582	0.3807	0.194	5.161	2581	2.77
	10	0.134	1.482	0.6803	0.0120	0.4582	0.3880	0.186	5.386	2693	2.53
	11	0.120	1.510	0.6145	0.0124	0.4582	0.3953	0.180	5.565	2783	2.29
	12	0.109	1.532	0.5620	0.0128	0.4582	0.4011	0.174	5.745	2873	2.09
	13	0.095	1.560	0.4939	0.0133	0.4582	0.4084	0.168	5.969	2985	1.84
	14	0.083	1.584	0.4346	0.0137	0.4582	0.4147	0.163	6.149	3075	1.62
	15	0.072	1.606	0.3796	0.0141	0.4582	0.4205	0.158	6.328	3169	1.41
	16	0.065	1.620	0.3441	0.0143	0.4582	0.4241	0.156	6.418	3209	1.28
	17	0.058	1.634	0.3083	0.0146	0.4582	0.4278	0.153	6.552	3276	1.15
	18	0.049	1.652	0.2619	0.0149	0.4582	0.4325	0.150	6.687	3344	0.974
	19	0.042	1.666	0.2253	0.0151	0.4582	0.4362	0.148	6.777	3389	0.838
1⅞	7	0.180	1.515	0.9585	0.0125	0.4909	0.3966	0.178	5.610	2805	3.57
	8	0.165	1.545	0.8884	0.0130	0.4909	0.4045	0.171	5.834	2917	3.30
	9	0.148	1.579	0.8030	0.0136	0.4909	0.4134	0.164	6.104	3052	2.99
	10	0.134	1.607	0.7329	0.0141	0.4909	0.4207	0.158	6.328	3164	2.73
	11	0.120	1.635	0.6616	0.0146	0.4909	0.4280	0.153	6.552	3276	2.46
	12	0.109	1.657	0.6048	0.0150	0.4909	0.4338	0.149	6.732	3366	2.25
	13	0.095	1.685	0.5312	0.0155	0.4909	0.4411	0.144	6.956	3478	1.98
	14	0.083	1.709	0.4594	0.0159	0.4909	0.4474	0.140	7.136	3568	1.74
	15	0.072	1.731	0.4078	0.0163	0.4909	0.4532	0.137	7.315	3658	1.52
	16	0.065	1.745	0.3695	0.0166	0.4909	0.4568	0.134	7.450	3725	1.38
	17	0.058	1.759	0.3310	0.0169	0.4909	0.4605	0.132	7.585	3793	1.23
	18	0.049	1.777	0.2811	0.0172	0.4909	0.4652	0.130	7.719	3860	1.05
	19	0.042	1.791	0.2418	0.0175	0.4909	0.4689	0.127	7.854	3927	0.900
2	7	0.180	1.640	1.0289	0.0147	0.5233	0.4294	0.152	6.597	3299	3.83
	8	0.165	1.670	0.9511	0.0152	0.5233	0.4372	0.147	6.822	3411	3.54
	9	0.148	1.704	0.8608	0.0158	0.5233	0.4461	0.141	7.091	3546	3.20
	10	0.134	1.732	0.7855	0.0164	0.5233	0.4534	0.136	7.360	3680	2.92
	11	0.120	1.760	0.7084	0.0169	0.5233	0.4608	0.132	7.585	3793	2.64
	12	0.109	1.782	0.6475	0.0173	0.5233	0.4665	0.129	7.764	3882	2.41
	13	0.095	1.810	0.5686	0.0179	0.5233	0.4739	0.125	8.034	4017	2.12
	14	0.083	1.834	0.4998	0.0183	0.5233	0.4801	0.122	8.213	4107	1.86
	15	0.072	1.856	0.4359	0.0188	0.5233	0.4859	0.118	8.437	4219	1.62
	16	0.065	1.870	0.3951	0.0191	0.5233	0.4896	0.117	8.572	4286	1.47
	17	0.058	1.884	0.3542	0.0194	0.5233	0.4932	0.115	8.707	4354	1.32
	18	0.049	1.902	0.3000	0.0197	0.5233	0.4979	0.113	8.841	4421	1.12
	19	0.042	1.916	0.2584	0.0200	0.5233	0.5016	0.111	8.976	4488	0.961

* B.W.G. = Birmingham wire gauge, commonly used for ferrous tubing; it is identical with Stubs' = Stubs' iron-wire gauge.

† In brass, sp gr = 8.56; sp gr of steel = 7.8.

CHAPTER G

HEAT TRANSFER

Heat transfer is important to all industry. Since it is of special importance to chemical plants, it would be desirable for all process engineers to be experts on heat transfer. The subject is so complex and comprehensive that all but a few engineers are well advised to depend on those more expert for the final design of critical heat-transfer equipment. This chapter presents data for estimating the simpler types of heat transfer. The accompanying discussion of theory is extremely brief and, alone, would not give the reader an adequate grasp of the subject. A few of the many excellent texts on the subject are listed below.

Schack, Goldschmidt, and Partridge, "Industrial Heat Transfer," John Wiley & Sons, Inc., New York, 1933.

McAdams, "Heat Transmission," 2d ed., McGraw-Hill Book Company, Inc., New York, 1942.

Stoever, "Applied Heat Transmission," McGraw-Hill Book Company, Inc., New York, 1941.

Croft, "Thermodynamics, Fluid Flow and Heat Transmission," McGraw-Hill Book Company, Inc., New York, 1938.

Badger, "Heat Transfer and Evaporation," Chemical Catalog Company, Inc., New York, 1926.

1. General Theory of Heat Flow

a. Types of Heat Transfer.—There are three principal mechanisms. *Radiation* is one that is familiar to anybody who has sat in the sun or stood in front of an open-hearth steel furnace. The heat is carried by radiation of visible and invisible light rays. Even cold objects emit some radiant energy which may be received by any object that is still colder.

Thermal conduction occurs wherever temperature inequalities exist. If a steel bar is heated on one end, the other end soon becomes warm.

Convection, the third method of thermal transfer, results from physical movement of matter. For example, the movement of hot air from a register carries heat into a cold room, and the heat reaches the far corners by the physical mixing of cold and warm air. Boiling liquids, condensing vapors, freezing liquids, and melting solids also involve movement of material and are classed as convection.

b. General Methods of Attack.—Several mechanisms proceed concurrently in most industrial heat transfer. For example, in a water heater, heat travels from the burning gases to the tube walls by radiation and convection, through the tube metal by conduction, and, finally, to the water by convection. If all the intermediate temperatures were known, the transfer of heat could be estimated from any one of the three steps. However, usually the intermediate conditions are unknown and all types of transfer must ultimately be treated together. This would be extremely difficult were it not that procedures have been developed that permit the calculations to be performed in steps.

The keys for understanding this division of operations are the concepts of thermal resistance and mean temperature difference. Thermal resistance is analogous to electrical resistance. It permits the definition of the over-all heat-transfer coefficient. The mean temperature difference has much the significance implied by the name and is a mathematical expedient of great utility. The procedures used vary with the nature of the particular problem and the preference of the worker. However, one method is below outlined in illustration:

1. Compute the material flows, and the rate of heat transfer required to accomplish task.
2. Compute temperature differences between the two fluids and from this compute the mean temperature difference.
3. Make a preliminary design of equipment. For example, if a tube and shell exchanger is proposed, choose the number, size, and spacing of the tubes and the baffle type and spacing.
4. Compute the fluid velocities from the results of (1) and (3) and estimate the film coefficients, metal resistance, and fouling factors involved in each step of heat transfer.
5. From these individual coefficients, estimate the over-all heat-transfer coefficient. This is done either by adding thermal resistances or by use of a formula based thereon.
6. From the results of (1), (2), and (5) compute the heat-transfer area (based on the external area of tubes or other appropriate surface) required.
7. Determine whether this surface can be secured with only modest changes from the preliminary design made in step (3). If so, the solution is complete.
8. If the result of (7) shows the preliminary design to be an impractical one, a new design must be made and steps (4) to (7) repeated.

2. Radiation

a. Thermal Radiation.—The laws governing the emission of radiant energy were derived by considering a "Hohlraum," a closed space filled only with the radiation in equilibrium with the walls. From the laws of thermodynamics and quantum mechanics the quantity (and also quality distribution of wave lengths) may be derived.

$$\frac{Q}{A} = 0.173\left(\frac{T}{100}\right)^4$$

where Q = Btu/hr (radiant energy *leaving* surface)
A = area of surface
T = absolute temperature, °R

If the surface is isolated and can receive no radiant energy from any source, the above equation gives the *maximum amount* that can be emitted and is termed the "black-body radiation." To secure the actual emission, the black-body radiation must be multiplied by an experimental factor called "emissivity."

In general, the engineer is not interested in isolated surfaces, but rather in the transfer of heat to or from one surface to others. In this case radiant energy is both emitted and absorbed. The net transfer is given by the following equation:

$$\begin{aligned} Q_1 &= 0.173A_1F\left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right] \qquad \text{(G-1)} \\ &= 0.173A_1F\left(\frac{T_1}{100}\right)^4 - 0.173A_1F\left(\frac{T_2}{100}\right)^4 \end{aligned}$$

where Q_1 = net radiant energy leaving surface 1, Btu/hr
A_1 = area of surface 1, sq ft
T_1 = temperature of surface 1, °R
T_2 = temperature of surface 2, °R
F = factor depending on emissivities and geometrical arrangement (see Table G-1)

This equation is based on the assumptions that the medium between the surfaces does not absorb any of the radiant energy and that the emissivity and absorptivity are the same. The factor F is evaluated from the surface emissivities and the laws of optics. Table G-1 permits computation for a few simple cases; values of emissivities are given in Table G-2. Figure G-1 will be found useful in calculations based on Eq. (G-1).

Very frequently radiant transfer is a small fraction of the total and may be neglected. Where radiation is a factor in heat exchangers, the radiant heat loss may be expressed as Btu/(hr)(sq ft) (°F) and added to the convection coefficient. This is done by guessing the unknown temperature, computing the radiation on that basis, and dividing the

TABLE G-1.—FACTORS FOR USE IN EQ. (G-1)

ϵ_1 = emissivity of surface 1

ϵ_2 = emissivity of surface 2

Arrangement of Surfaces	Emissivity Factor, F
Surface 1 small compared to surface 2 (for example, heat loss of equipment to surroundings)	ϵ_1
Two parallel planes of equal area when length and breadth are large compared to distance between them	1
Surface 1 is cylinder (radius = r_1) inside larger concentric cylinder (radius = r_2) when length is large compared to diameter	$\frac{1}{\epsilon_1} + \frac{r_1}{r_2}\left(\frac{1}{\epsilon_2} - 1\right)$
Surface 1 is sphere (radius = r_1) inside of concentric sphere (radius = r_2)	$\dfrac{1}{\frac{1}{\epsilon_1} + \left(\frac{r_1}{r_2}\right)^2\left(\frac{1}{\epsilon_2} - 1\right)}$

NOTE: Factors based on surface separated by transparent medium.

TABLE G-2.—EMISSIVITIES OF SURFACES

Surface	Temperature, °F	Emissivity
Dull brass	120–660	0.22
Oxidized copper	77	0.78
Rolled sheet steel	70	0.66
Oxidized iron	67	0.74
Cast plate, smooth	73	0.80
Brick:		
Building	....	0.80–0.95
Refractory	....	0.75–0.90
Aluminum paint	....	0.3–0.6
Oil paint	212	0.92–0.96
Roofing paper	69	0.91

rate by the temperature difference. This expedient is mathematically unsound but is a justifiable approximation, provided the assumed temperature is reasonably close to that found by a final computation.[1]

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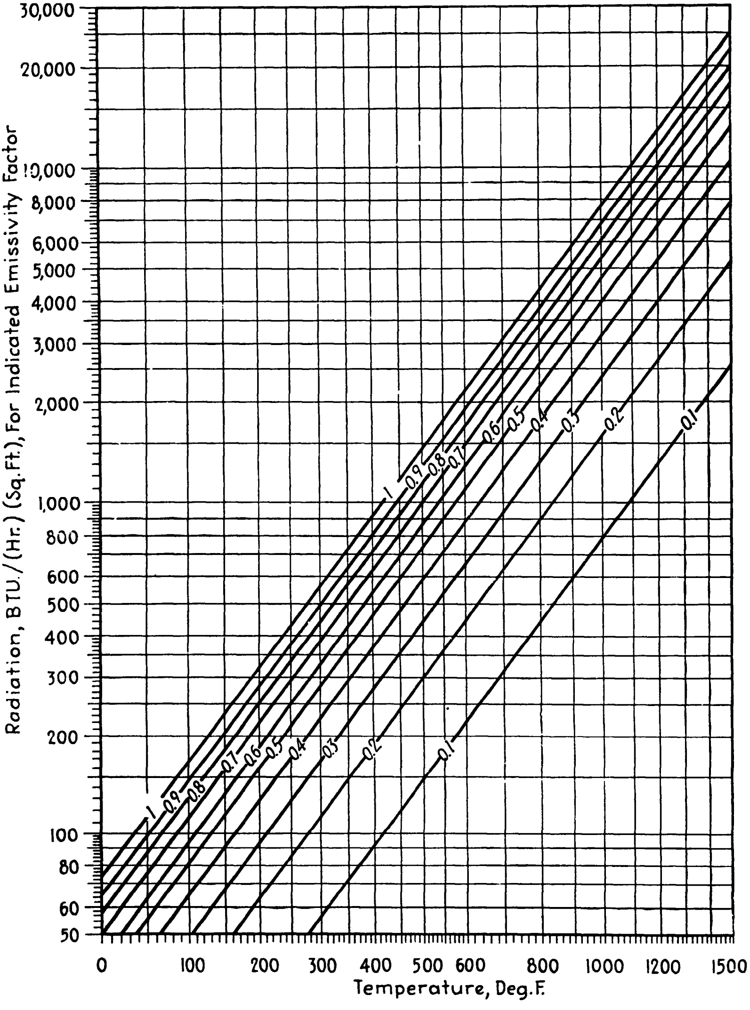
[1] See McAdams, "Heat Transmission," 2d ed., McGraw-Hill Book Company, Inc., New York, 1942, for a complete discussion.



NOTE: Loss = Radiation at surface temperature less radiation at surrounding temperature [see Eq. (G-1)].

FIG. G-1.—Chart for computing radiation losses.

b. Solar Radiation.—During the day, open equipment is heated by sunlight. Figure G-2 gives data on solar radiation and may be used for the estimation of the maximum heating effect of the sun on clear days. The fraction of this absorbed depends on the absorptivity which may be taken as equal to the emissivity for approximate calculations. Table G-3 gives experimental values of the rise in temperature produced on different surfaces exposed to the sun.

TABLE G-3.—DAILY MEAN RISE IN TEMPERATURE OF TEST PANELS EXPOSED TO THE SUN

(*Nat. Bur. Standards, Building Materials and Structures Report* BMS64)

	Aug. 2, 1939	Aug. 3, 1939	Aug. 1, 1939	July 31, 1939	Aug. 7, 1939
Panel inclination from horizontal, deg	90	90	60	45	30
	°F	°F	°F	°F	°F
Black (lampblack)	20.9	21.0	37.4	46.3	48.5
Galvanized iron	16.1	15.3	28.1	32.0	37.7
Roofing shingle:					
Aluminum	19.4	20.2	34.1	40.7	41.6
Green	19.5	20.7	33.3	41.3	43.4
Red	21.5	23.1	37.2	44.8	46.0
Aluminum foil	9.8	8.3	15.0	17.3	19.7
White road-marking paint	12.3	12.1	19.7	22.9	24.7
Aluminum paint	14.6	14.5	24.4	29.0	29.3
Glossy white paint	8.9	7.9	12.1	13.0	15.5
Flat white paint	9.1	8.3	13.2	15.6	17.2
Ivory paint	10.2	9.3	14.9	16.8	19.2
Canary-yellow paint	10.9	10.4	16.7	19.2	21.6
Pearl-gray paint	13.3	13.7	20.3	24.3	25.6
Silver-gray paint	13.9	14.2	20.3	24.6	26.3
Light lead paint	15.1	15.2	22.9	27.4	29.7
Slate paint	16.8	17.1	26.7	32.4	35.4
Medium-green paint (trim color)	20.4	20.5	35.3	42.7	46.3

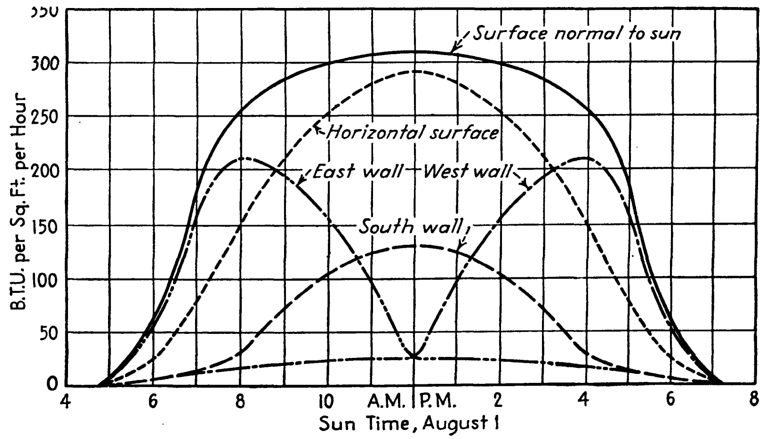


FIG. G-2.—Solar intensity normal to sun on horizontal surface and on walls for Aug. 1 at 40 deg North latitude. (*Reprinted from Heating Ventilating Air Conditioning Guide* 1942, *p.* 144.)

3. Conduction

a. Steady Conduction.—If two faces of a solid are maintained at different fixed temperatures, heat will flow through the metal at a steady rate. Most industrial heat-exchange equipment operates under conditions of steady heat conduction; that is, local temperatures and heat-flow rates change but slowly from one hour to the next. The relations for steady conduction reduce to the following very simple basic equation:

$$\frac{dQ}{dA} = -k\frac{dt}{dx} \tag{G-2}$$

where Q = heat flow, Btu/hr
A = area at right angles to direction of heat flow, sq ft
t = temperature, °F
x = position relative to any fixed plane, and measured in the direction of heat flow, ft
k = thermal conductivity, Btu/(hr) (sq ft) (°F/ft)

Equation (G-2) may readily be integrated over the volume of the body to obtain the over-all transfer through it. For the two most common cases it becomes

$$Q = -kA\frac{\Delta t}{L} \qquad \text{(slab of large area)} \tag{G-3}$$

$$Q = -k\frac{A_0 - A_i}{\ln (A_0/A_i)}\frac{\Delta t}{L} \qquad \text{(long pipe)} \tag{G-4}$$

$$= -kA_m\frac{\Delta t}{L}$$

where Q = heat transferred, Btu/hr
k = thermal conductivity, Btu/(hr) (sq ft) (°F/ft)
A = surface area slab, sq ft
A_0 = outside area pipe, sq ft
A_i = inside area pipe, sq ft
A_m = logarithmic mean of A_0 and A_i, sq ft (A_m may be computed by Fig. G-13)
Δt = temperature difference between hot and cold side of wall, °F
L = wall thickness, ft

Equation (G-2) may also be used when the heat conduction is through several layers of different materials. Integrations in the case of slabs and pipes are given below:

$$Q = A\Delta t\frac{1}{\frac{L_1}{k_1} + \frac{L_2}{k_2} + \frac{L_3}{k_3} + \cdots} \tag{G-5}$$

$$Q = \Delta t \frac{1}{\frac{L_1}{k_1 A_1} + \frac{L_2}{k_2 A_2} + \frac{L_3}{k_3 A_3} + \cdots} \tag{G-6}$$

where Q = heat transferred, Btu/hr
Δt = temperature difference between hottest and coldest surface
L_1, L_2, L_3 = thickness of layers 1, 2, 3, ft
k_1, k_2, k_3 = thermal conductivities, Btu/(hr) (sq ft) (°F/ft) of layers
A = slab area, sq ft
A_1, A_2, A_3 = logarithmic mean area of pipe components of layers 1, 2, 3, sq ft

b. Thermal Conductivity Data.—Table G-4 gives data on metals and Table G-5 gives conductivities of insulating materials.

TABLE G-4.—THERMAL CONDUCTIVITIES OF METALS
Values given in Btu/(hr)(sq ft)(°F/ft)
Values given in parentheses are extrapolated more than 50°F

Metal	Temperature, °F								Reference
	0	100	200	300	400	600	800	1000	
Aluminum	116	117	118	121	124	134	147	.....	1, 2
Brass (70% Cu)	55	58	60	62	63	66	67	.....	1
Cast iron	(33)	(32)	31	30	29	28	26	(23)	3
Cast high-silicon iron	....	(30)	....	....	....	....	....	.....	1
Copper (pure)	225	222	219	217	215	211	209	206	1
Iron (99.9%)	(42)	(40)	38	37	35	32	28	24	3
Lead	21	20	19	18	18	....	....	.....	1, 2
Nickel	37	35	34	33	33	32	....	.....	1
Monel	...	15	....	....	....	....	....	.....	4
Steel:									
0.1% C	(36)	35	33	30	28	26	24	23	2, 4
0.8% C (quenched)	...	(24)	24	24	23	23	21	.....	3
18-8 Cr-Ni (low C)	(8.5)	(9.0)	9.4	9.8	10.2	11.0	11.8	(12.6)	3
0.35% C, 1% W	(23)	(22)	22	21	21	19	....	.....	3
12% Cr	....	(13.8)	14.0	14.2	14.3	14.6	14.9	(15.3)	3
Wrought iron	(36)	(35)	33	31	31	28	25	(23)	3

NOTE: Additional data on a few other metals are given in Table D-2.

REFERENCES:

1. Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York, 1941.
2. Schack, Goldschmidt, and Partridge, "Industrial Heat Transfer," John Wiley & Sons, Inc., New York, 1933.
3. Shelton, *J. Research, Nat. Bur. Standards*, **12**, 441 (1934).
4. "Heat Transfer through Metallic Walls," International Nickel Co., New York.

TABLE G-5. SOME PHYSICAL AND THERMAL CHARACTERISTICS OF COMMERCIAL
(Saginor, *Chem. & Met. Eng.* January, 1941)

Material	Commercial forms available	Upper limiting temp., °F	Density, lb/cu ft	Thermal conductivity, Btu/(hr)(sq ft)(°F/in.), at mean temperature, °F											
				100	200	300	400	500	600	800	1000	1200	1500	2000	2500
Aluminum foil	Built-up sectional and block	1000	0.2	0.28	0.37	0.39	0.46	0.52	0.58						
Asbestos	Loose fiber	800	36	0.16	1.23	1.40	1.45	1.48	1.50	1.56					
Asbestos finishing cements	Loose dry	1000	48–60	....	1.50										
Asbestos air cell	Sectional and block														
	4 plies per in.	300	12	0.53	0.65	0.77	0.89								
	8 plies per in.	300	19	0.48	0.56	0.63	0.71								
Asbestos felts (sponge felt)	Sectional and block														
	40 laminations per in.	700	30	0.40	0.44	0.49	0.53	0.59							
	20 laminations per in.	700	20	0.55	0.61	0.67	0.73	0.79							
Asbestos millboard	Sheets	1000	54	0.90	0.95	1.00	1.20	1.40	1.50						
Asbestos sprayed	Loose fiber and liquid binder	800	7	0.36	0.41	0.46	0.53	0.63							
Concrete—insulating type	Loose granular	1800	31	1.72	1.80	1.87	1.94	2.01	2.08	2.23	2.37	2.51	2.73	3.43	
Concrete—insulation refr'y	Powder	2200	65	....	....	2.78	2.82	2.86	2.90	2.98	3.09	3.20	3.44	3.84	
Cork	Sectional and block	200	11	0.30											
Diatomaceous earth	Fine powder	1600	15–17	0.38	0.41	0.44	0.48	0.51	0.55	0.62	0.69	0.76	0.86		
	Coarse powder	1600	22	0.45	0.48	0.52	0.55	0.59	0.62	0.70	0.77	0.84	0.95		
High temp. alumina and diatomac. silica mixtures	Sectional and block	1900–2000	24–30	....	0.59	0.61	0.64	0.68	0.70	0.76	0.82	0.88			
Hair felt	Blanket	200	13	0.30											
Silica brick	Brick	3100–3300	130–150	6.20	6.50	6.80	7.00	7.30	7.60	8.20	8.80	9.40	10.20	11.70	13.20
Firebrick	Brick	2250–3200	110–112	5.80	6.00	6.20	6.50	6.70	6.90	7.40	7.80	8.30	9.00	10.20	11.30
Red brick	Brick	500–1000	100–120	4.50	4.70	5.00	5.20	5.50	5.80	6.30	6.80	7.30	8.10		
Insulating brick	Brick	2500	39–53	....	1.57	1.73	1.84	2.01	2.14	2.50	2.53	2.83			

TABLE G-5.—SOME PHYSICAL AND THERMAL CHARACTERISTICS OF COMMERCIAL INSULANTS (*Continued*)

Material	Commercial forms available	Upper limiting temp., °F	Density, lb/cu ft	Thermal conductivity, Btu/(hr)(sq ft)(°F/in.), at mean temperature, °F											
				100	200	300	400	500	600	800	1000	1200	1500	2000	2500
Insulating brick	Brick	2000	28–38	....	1.12	1.15	1.19	1.23	1.27	1.37	1.48	1.62			
Insulating brick	Brick	1600	30	....	0.78	0.81	0.85	0.89	0.93	1.00	1.09	1.16			
Kapok	Blanket	212	1	0.25											
Magnesia—85 %	Sectional and block	600	17	0.43	0.47	0.51	0.55								
Magnesia cements	Loose dry	600	21	0.48	0.54	0.60	0.66								
Mineral wools (untreated):*															
Glass wool	Loose, flexible		3	0.26	0.32	0.41	0.61								
	Sectional and blanket	1000	4	0.24	0.30	0.38	0.52								
			8	0.22	0.26	0.30	0.36								
Rock wool	Loose, flexible		5	0.29	0.37	0.47	0.64								
	Sectional and blanket	1000	10	0.28	0.33	0.39	0.46								
			15	0.29	0.35	0.40	0.47								
			20	0.34	0.38	0.43	0.49								
Slag wool	Loose, flexible														
	Sectional and blanket	1000	Generally same as rock wool												
Mineral-wool-type cements	Loose dry	1500	24–30	0.57	0.61	0.66	0.77	0.88	1.02	1.15	1.44				
Mineral wool (waterproofed low temperature type)	Board	225	18	0.36											
	Sectional and block	165	15	0.30											
	Blanket	225	16	0.29											
Vermiculite	Loose, sectional, and block	1600	17	0.57	0.64	0.69	0.73	0.76	0.80	0.89	0.98				
Vermiculite-type cements	Loose dry	1800	16	0.74	0.79	0.84	0.89	0.94	1.04	1.14	1.25				
Wool felt	Sectional or block	212	24	0.36											

NOTE: Conductivity figures represent average value of commercial makes of various manufacture. Conductivity of cements, loose fills, and flexible insulants varies with applied density.

* Some manufacturers recommend 1200°F limit for mineral wools.

c. Heating and Cooling of Solids.—The basic equation for the general case of heat flow by conduction is

$$\frac{\rho C_p}{k}\frac{\partial t}{\partial \theta} = \frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} + \frac{\partial^2 t}{\partial z^2}$$

where t = local temperature, °F, at time θ
ρ = density, lb/cu ft
C_p = specific heat, Btu/(lb) (°F)
k = thermal conductivity, Btu/(hr) (sq ft) (°F/ft)
x, y, z = Cartesian coordinates

This equation must be handled by the comparatively complex methods of partial differential equations. Figure G-3 plots solutions of this equation for several shapes of solids under the assumption of a constant surface temperature. This figure may be used to estimate cooling rates as follows:

1. Compute $\frac{k\theta}{\rho C D^2}$

where k = thermal conductivity, Btu/(hr)(sq ft)(°F/ft)
C = specific heat, Btu/(lb)(°F)
θ = time of cooling or heating, hr
ρ = density of solid, lb/cu ft
D = dimension as indicated in Fig. G-3.

2. From Fig. G-3 find corresponding value of

$$\frac{t_1 - t}{t_1 - t_0}$$

where t_0 = original temperature
t_1 = surface temperature
t = temperature at center at time θ

3. From numerical values solve for t.

$$\begin{aligned} t &= t_1 - (t_1 - t_0)x \text{ heating} \\ &= t_1 + (t_0 - t_1)x \text{ cooling} \end{aligned}$$

where x = numerical value $(t_1 - t)/(t_1 - t_0)$ read from Fig. G-3

It should be noted that the assumption of constant surface temperature is seldom precisely fulfilled but is determined by the rate of removal of heat from the surface. If the rate of removal is very rapid, Fig. G-3 will give fair accuracy. For a more complete treatment, the reader is referred to McAdams.[1]

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[1] *Op. cit.*

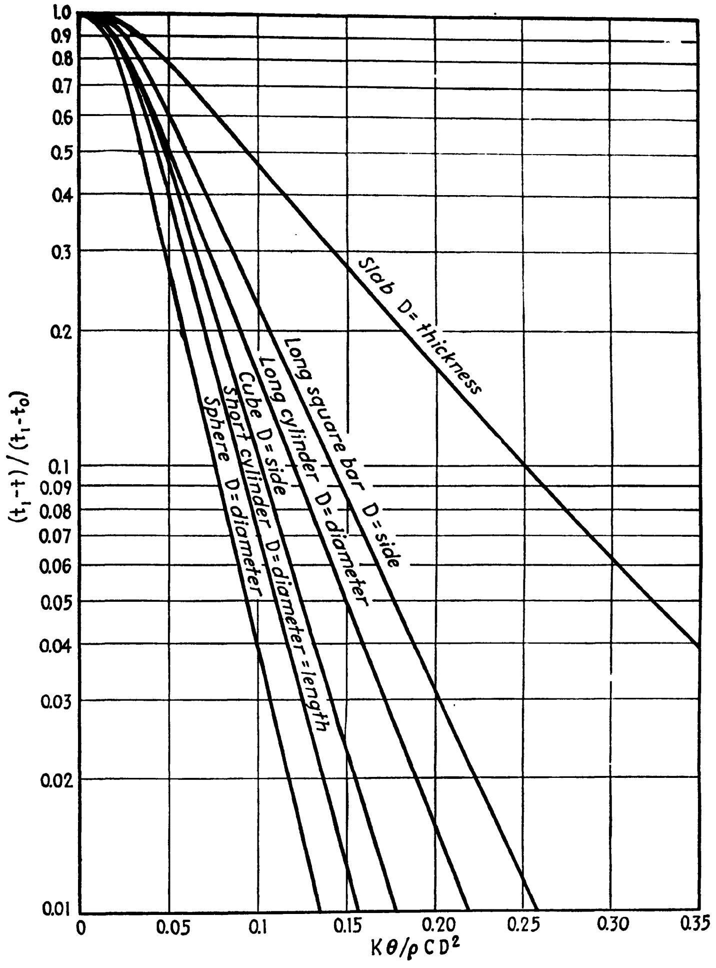

FIG. G-3.—Heating or cooling of solids. [*After Williamson and Leason, Phys. Rev.* **14**, 99 (1919).]

4. Convection Coefficients

a. Theory.—There are two types of fluid flow: laminar (or streamline) and turbulent. These were discussed in Chapter F. As might be expected, heat-transfer relationships depend on which type of fluid flow is involved. Unless liquids of high viscosity are being handled, the flow is usually turbulent in commercial exchangers. Information given in this chapter is confined largely to the turbulent conditions.

The differential equations for transfer of heat by turbulent flow have been set up but are too complex to be solved directly. Using the theory of similarity, Nusselt, Prandtl, and others have shown that these equations would give similar solutions when certain dimensionless groups have the same values. These conclusions have been verified and extended by the methods of dimensional analysis and, more important, by experimental data. The rate of heat transfer may be expressed in any one of several ways. By far the most convenient of these is the surface conductivity, or film, coefficient. (The former term, in some respects, more closely expresses the significance of the coefficient, but the latter term has received wide usage and will be employed here.) This film coefficient expresses the heat transfer per unit of boundary surface and difference in temperature between the bulk of the fluid and the boundary surface. The conclusions of theory for fluids inside tubes may be expressed as follows:

$$h = \frac{k}{D_e} f(R_e, P_r) \qquad \text{(G-7)}$$

where h = film coefficient, Btu/(hr)(sq ft)(°F)
k = thermal conductivity, Btu/(hr)(sq ft)(°F/ft)
D_e = equivalent diameter, ft
= diameter for circular tube
$= 4 \times \dfrac{\text{area}}{\text{perimeter}}$ (see Table F-4)
R_e = Reynolds number [see Eq. (F-10) repeated below]
P_r = Prandtl number [see Eq. (G-8) below]
f denotes a functional relationship to quantities following

$$R_e = \frac{D_e u \rho}{\mu_e} = \frac{D_e G}{\mu_e} = \frac{124 d_e u \rho}{\mu} = \frac{50.7 m \rho}{\mu d} = \frac{6.32 W}{\mu d} \qquad \text{(F-10)}$$

where D_e = equivalent diameter, ft
d_e = equivalent diameter, in.
d = diameter of circular pipe, in.
u = average velocity, fps
μ_e = viscosity, lb/(ft)(sec)
G = mass velocity, lb/(sq ft)(sec)
μ = viscosity, centipoise
m = flow, gpm
W = flow, lb/hr
ρ = density, lb/cu ft

$$P_r = \frac{c_p \mu_e}{k_s} = 2.42 \frac{c_p \mu}{k} \qquad \text{(G-8)}$$

where c_p = specific heat, Btu/(lb)(°F)
μ_e = viscosity, lb/(ft)(sec)
μ = viscosity, centipoise
k = thermal conductivity, Btu/(hr)(sq ft)(°F/ft)
k_s = thermal conductivity, Btu/(sec)(sq ft)(°F/ft)

The equivalent diameter, as defined above, is based on the "wetted perimeter." This is consistent with the best hydraulic practice. Nusselt suggested that the equivalent diameter for thermal transfer be based on the "heated perimeter" instead. However, recent experiments[1] indicate that the "wetted perimeter" is in the smaller error.

Experiments are essential to evaluate the form of the functional relationship indicated by Eq. (G-7). Results can be expressed as follows:

$$h = a \frac{k}{D_e} R_e^b P_r^c \tag{G-9}$$

where h = film coefficient
k = thermal conductivity
D_e = equivalent diameter
R_e = Reynolds number [see Eq. (F-10)]
P_r = Prandtl number [see Eq. (G-8)].
a = a constant dependent on units of h, k, D_e
b, c = constants

The constants in Eq. (G-9) are dependent on geometrical arrangements and whether the fluid is heated or cooled, but they are independent of the physical properties of the fluid handled. That is, one equation may be used for all fluids being cooled in straight tubes; another equation may be used for all fluids being heated by flow across a bank of tubes, etc. Equations given in this chapter are rearranged from the dimensionless form indicated above to dimensional equations for convenience in computation.

Similar types of consideration enter into the theoretical treatment of condensing vapors and boiling liquids. The relations that result, however, are considerably different in form.

b. Gases.—Film coefficients of gases may be expressed in a very simple form because the Prandtl number is nearly constant and because the viscosity factors do not vary greatly. The resulting relations follow. Figure G-4 presents inside coefficients in nomograph form.

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[1] Carpenter, Colburn, Schoenborn, and Wurster, *Trans. Am. Inst. Chem. Engr.*, **42**, 165 (1946).

Inside tubes:

$$h = 16.6c_p \frac{G^{0.8}}{d_e^{0.2}} \qquad \text{(G-10)}$$

Outside tubes:

Based on true velocity,

$$h = 44F_nc_p \frac{G_o^{0.6}}{d_o^{0.4}} \qquad \text{(G-11)}$$

Based on calculated velocity,

$$h = 26F_nc_p \frac{G_c^{0.6}}{d_o^{0.4}} \qquad \text{(G-12)}$$

where h = film coefficient, Btu/(hr)(sq ft)(°F)
c_p = specific heat, Btu/(lb)(°F)
G = mass velocity inside tube or annulus, lb/(sec)(sq ft)
$= \frac{W}{25A} = \frac{W}{12.63d^2}$
W = flow, lb/hr
A = cross-sectional area of tube or annulus, sq in.
d_e = equivalent diameter inside tube or annulus, in.
$= 4 \times \frac{\text{area}}{\text{perimeter}}$ (see Table F-4)
$= d$ = inside diameter of circular tube, in.
F_n = factor depending on number of rows of tubes (see Table G-6)
= 1 for 10 or more staggered rows
= 0.8 for 10 or more rows in line
G_o = true mass velocity across tubes at point of closest distance between the tubes, lb/(sec)(sq ft)
G_c = calculated mass velocity neglecting leakage between baffles (shell and tube exchangers), lb/(sec)(sq ft)
$= \frac{WS}{25BD(S - d_o)}$ for half-moon baffles
S = center-to-center spacing of tubes, in.
B = baffle spacing, in.
D = inside diameter of shell, in.
d_o = outside diameter of tubes, in.

It will be noted that the only temperature and pressure dependence afforded by these equations is the value of the specific heat. This is a reasonably accurate correction, but it is largely untested at very high pressures and temperatures. For these conditions, or where high accuracy is desired, Eq. (G-13), page 252, would be preferred.

TABLE G-6.—CORRECTION FACTORS FOR USE IN EQ. (G-11) AND (G-12) FOR HEAT TRANSFER OF FLUIDS ACROSS LESS THAN 10 ROWS OF TUBES
(Based on data of McAdams, "Heat Transmission," 2d ed., McGraw-Hill Book Company, Inc., New York, 1942)

Number of rows	1	2	3	4	5	6	8	10 or more
Staggered.......	....	0.73	0.82	0.88	0.91	0.94	0.98	1.00
In line..........	0.51	0.64	0.69	0.72	0.74	0.76	0.78	0.80

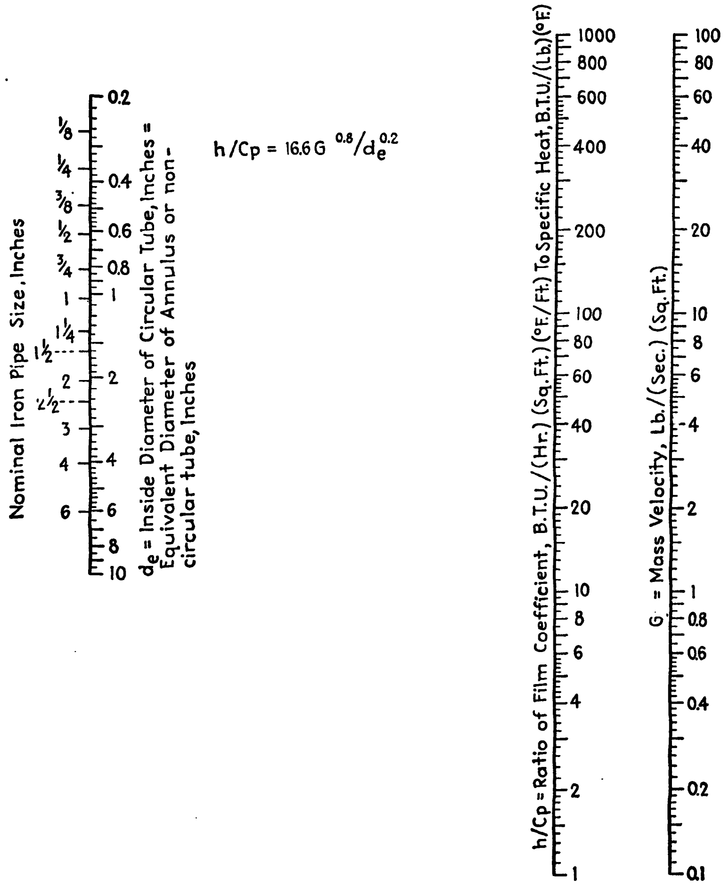
Nominal Iron Pipe Size, Inches
1/8
1/4
3/8
1/2
3/4
1
1 1/4
1 1/2
2
2 1/2
3
4
6
0.2
0.4
0.6
0.8
1
2
4
6
8
10
d_e = Inside Diameter of Circular Tube, Inches = Equivalent Diameter of Annulus or non-circular tube, Inches
$h/Cp = 16.6\,G^{0.8}/d_e^{0.2}$
h/Cp = Ratio of Film Coefficient, B.T.U./(Hr.)(Sq.Ft.)(°F./Ft.) To Specific Heat, B.T.U./(Lb.)(°F.)
1000
800
600
400
200
100
80
60
40
20
10
8
6
4
2
1
G = Mass Velocity, Lb./(Sec.)(Sq.Ft.)
100
80
60
40
20
10
8
6
4
2
1
0.8
0.6
0.4
0.2
0.1

FIG. G-4.—Film coefficients for gases in turbulent flow inside tubes.

c. Charts for Liquids.—Stoever has prepared a number of tables and charts for computation. This section presents his data on liquids in unchanged form (Tables G-7 to G-11 and Figs. G-5 to G-10, etc.). This section comprises his cases 1 to 7 with cases 9 and 10.

FILM COEFFICIENTS FOR LIQUIDS

(Stoever, *Chem. & Met. Eng.*, May, 1944.)

To obtain the desired film coefficient, a base factor corresponding to the liquid and temperature under consideration is taken from the proper table and multiplied by a correction factor read from the nomograph accompanying that table. The following assumptions apply in each case: (1) the system is in equilibrium, that is, there is no change in temperature gradient with time; (2) radiation is negligible or has been taken into account by other calculations; (3) film temperature is defined as the arithmetic average of the temperatures of the retaining wall and the main body of the liquid. Wall temperature, generally not known, can be estimated or calculated by trial and error. Values of base factors in italics are extrapolated from physical properties.

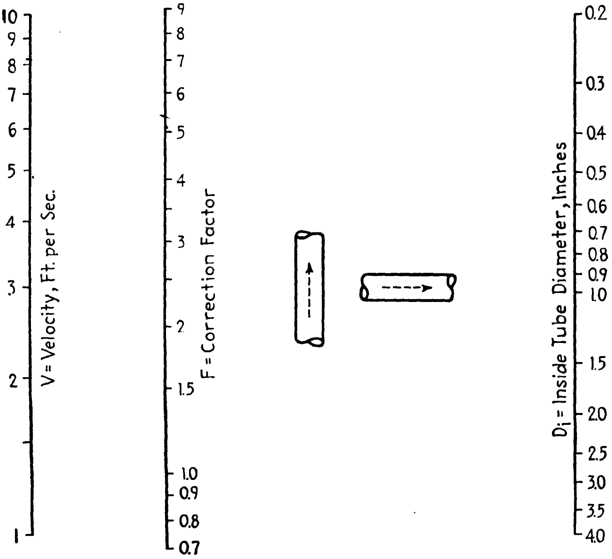

FIG. G-5.—Case 1, correction factors for liquids heated inside tubes. (*Stoever, Chem. and Met. Eng., May, 1944.*)

TABLE G-7

CASE 1.—BASE FACTORS FOR LIQUIDS HEATED INSIDE HORIZONTAL OR VERTICAL TUBES, TURBULENT FLOW

	Average temperature of the liquid					
	0°F	50°F	100°F	150°F	200°F	250°F
Acetic acid (100%)	....	....	97.2	101	*105*	*109*
Acetic acid (50%)	....	117	156	180	203	*228*
Acetone	*104*	122	134	137	*139*	*142*
Ammonia	350	425	507	*599*	*690*	*790*
Amyl acetate	65.0	66.2	67.7	71.8	*78.5*	*86.0*
Amyl alcohol (*iso*)	*21.6*	35.8	52.7	73.3	96.0	*118*
Aniline	....	43.8	58.4	76.5	99.2	*123*
Benzene	....	75.6	94.5	108	121	*134*
Brine ($CaCl_2$)(25%)	139	190	257	332	420	*517*
Butyl alcohol (*n*)	*31.2*	45.5	62.4	83.0	*107*	*133*
Carbon disulphide	114	119	125	129	*132*	*133*
Carbon tetrachloride	*57.4*	69.2	78.6	82.6	*85.8*	*88.2*
Chlorobenzene	*64.6*	73.3	78.8	80.5	82.0	*82.8*
Ethyl acetate	*126*	126	125	123	*122*	*121*
Ethyl alcohol (100%)	58.0	73.6	92.3	112	132	*151*
Ethyl alcohol (40%)	*61.5*	104	162	*228*	*292*	*389*
Ethyl bromide	*97.8*	104	110	114	*119*	*122*
Ethylene glycol	*71.4*	105	158	222	299	*380*
Ethyl ether	*100*	115	123	130	*137*	*144*
Glycerol (50%)	*59.0*	90.5	131	*182*	*242*	*302*
Heptane	*81.4*	87.0	94.7	102	*112*	*122*
Hexane	*85.8*	93.8	102	109	114	*117*
Methyl alcohol (100%)	*83.0*	110	126	*138*	*149*	*160*
Methyl alcohol (90%)	*86.0*	114	136	*154*	*172*	*188*
Methyl alcohol (40%)	*64.0*	110	164	213	*264*	*312*
Octane (*n*)	*72.0*	79.0	85.9	*92.0*	*97.0*	*102*
Pentane (*n*)	103	105	110	*115*	*118*	*121*
Propyl alcohol (*iso*)	*25.7*	49.3	71.5	94.5	*117*	*139*
Sulphur dioxide	167	171	175	*180*	*182*	*194*
Sulphuric acid (60%)	....	65.9	79.4	94.5	*110*	*129*
Toluene	77.3	86.9	96.6	104	112	*119*
Water	....	225	322	408	392	*508*

TABLE G-8

CASE 2.—BASE FACTORS FOR LIQUIDS COOLED INSIDE HORIZONTAL OR VERTICAL TUBES, TURBULENT FLOW

	Average temperature of the liquid					
	0°F	50°F	100°F	150°F	200°F	250°F
Acetic acid (100%)	....	....	72.2	75.0	*78.7*	*81.6*
Acetic acid (50%)	....	85.2	122	153	179	*201*
Acetone	*88.4*	105	118	121	*124*	*126*
Ammonia	314	380	507	*650*	*797*	*938*
Amyl acetate	48.1	50.7	52.3	53.3	*54.4*	*55.5*
Amyl alcohol (*iso*)	....	22.7	36.0	53.0	72.3	*91.8*
Aniline	....	31.6	45.2	63.3	86.9	*110*
Benzene	....	61.7	79.1	93.5	107	*120*
Brine ($CaCl_2$)(25%)	106	152	217	312	397	*510*
Butyl alcohol (*n*)	*19.2*	31.4	45.6	64.0	*84.9*	*107*
Carbon disulphide	103	110	116	121	*126*	*128*
Carbon tetrachloride	*40.4*	55.8	67.3	72.0	*76.0*	*78.7*
Chlorobenzene	*54.5*	57.5	60.7	63.8	65.0	*65.6*
Ethyl acetate	*83.3*	84.1	84.1	84.1	*83.3*	*82.4*
Ethyl alcohol (100%)	41.2	54.8	71.1	89.0	108	*128*
Ethyl alcohol (40%)	....	70.4	121	*176*	*230*	*315*
Ethyl bromide	*84.9*	92.9	99.9	106	*112*	*116*
Ethylene glycol (50%)	*44.2*	71.7	120	183	261	
Ethyl ether	*86.0*	99.0	109	118	*126*	*135*
Glycerol (50%)	*34.9*	59.5	94.5	*134*	*179*	*222*
Heptane	*66.8*	74.2	81.5	88.8	*97.0*	*104*
Hexane	*70.7*	78.5	87.2	95.2	102	*108*
Methyl alcohol (100%)	*65.4*	88.5	105	*118*	*132*	*146*
Methyl alcohol (90%)	*68.5*	92.0	112	*128*	*142*	*156*
Methyl alcohol (40%)	*38.2*	80.0	127	177	*236*	*292*
Octane (*n*)	*56.0*	63.8	70.9	*77.2*	*82.2*	*88.0*
Pentane (*n*)	82.8	89.6	96.4	*101*	*106*	*110*
Propyl alcohol (*iso*)	....	32.4	51.5	71.7	*92.7*	*116*
Sulphur dioxide	150	155	161	*166*	*174*	*178*
Sulphuric acid (60%)	....	35.3	54.4	66.9	*74.0*	*77.7*
Toluene	61.8	71.5	81.4	90.3	97.6	*103*
Water	....	153	273	355	427	*483*

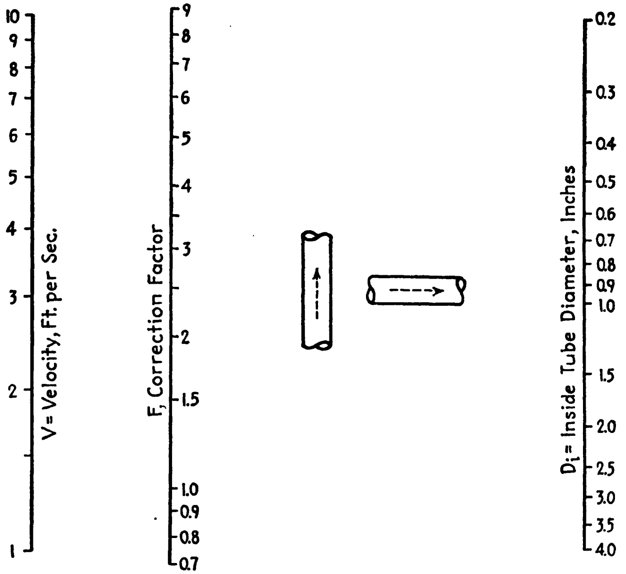

FIG. G-6.—Case 2, correction factors for liquids cooled inside tubes. (*Stoever, Chem. and Met. Eng., May,* 1944.)

CASE 3.—LIQUIDS HEATED OR COOLED OUTSIDE TUBE BUNDLES, DIRECTION OF FLOW PARALLEL TO TUBES

Film coefficients for liquids flowing outside tube bundles and in a direction parallel to the tubes can be determined from Cases 1 or 2 for liquids inside tubes, if an equivalent inside diameter is used in determining the correction factor. An equivalent diameter can be calculated by the following equation:

$$d_e = 4 \times A/P$$

where d_e = equivalent inside diameter., in.

A = cross-sectional area between tubes, sq in.

P = sum of the tube perimeter segments bounding the cross-section, in.

For tubes based on equilateral triangles, or on squares, d_e can be read from Fig. G-7.

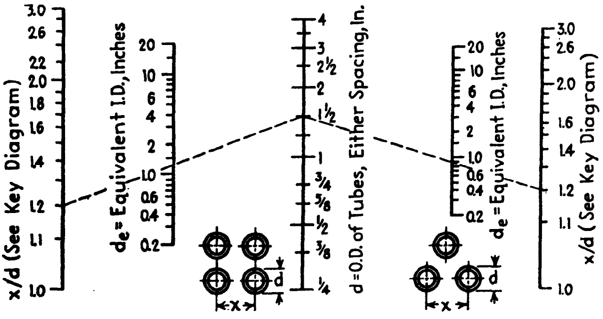

FIG. G-7.—Case 3, equivalent diameters for flow of liquids outside of tube bundles, direction of flow parallel to tubes. (*Stoever, Chem. and Met. Eng., May,* 1944)

TABLE G-9

CASE 4.—BASE FACTORS FOR LIQUIDS HEATED OR COOLED OUTSIDE SINGLE TUBES, DIRECTION OF FLOW NORMAL TO TUBE

	Average temperature of the film					
	0°F	50°F	100°F	150°F	200°F	250°F
Acetic acid (100%)	....	....	142	136	*131*	*125*
Acetic acid (50%)	....	214	260	292	310	*321*
Acetone	*165*	174	184	186	*187*	*189*
Ammonia	486	548	616	*685*	*758*	*827*
Amyl acetate	114	106	97.9	91.0	*84.3*	*76.5*
Amyl alcohol (*iso*)	*54.0*	73.0	94.9	118	140	*163*
Aniline	....	97.0	116	139	164	*194*
Benzene	....	124	140	152	163	*174*
Brine ($CaCl_2$)(25%)	264	335	419	508	617	*734*
Butyl alcohol (*n*)	*93.5*	100	112	136	*167*	*206*
Carbon disulphide	164	166	169	171	*173*	*173*
Carbon tetrachloride	....	105	114	116	*117*	*118*
Chlorobenzene	*115*	112	109	106	103	*102*
Ethyl acetate	*154*	145	137	129	*119*	*111*
Ethyl alcohol (100%)	*108*	127	146	165	183	*199*
Ethyl alcohol (40%)	*130*	199	277	*355*	*430*	*508*
Ethyl bromide	*131*	137	142	144	*146*	*147*
Ethylene glycol (50%)	*147*	209	283	362	447	*545*
Ethyl ether	*146*	154	161	169	*175*	*182*
Glycerol (50%)	*147*	192	249	*331*	*431*	
Heptane	*126*	133	139	143	*147*	*151*
Hexane	*128*	134	141	147	151	*155*
Methyl alcohol (100%)	*147*	170	187	*198*	*206*	*212*
Methyl alcohol (90%)	*159*	186	209	*226*	*238*	*251*
Methyl alcohol (40%)	*132*	201	264	317	*359*	*397*
Octane (*n*)	*117*	124	129	*135*	*140*	*146*
Pentane (*n*)	139	144	148	*151*	*152*	*154*
Propyl alcohol (*iso*)	*62.5*	91.0	118	143	163	*180*
Sulphur dioxide	230	225	223	*221*	*221*	*218*
Sulphuric acid (60%)	....	*110*	137	150	164	*176*
Toluene	128	135	142	148	152	*155*
Water	....	382	497	575	645	*700*

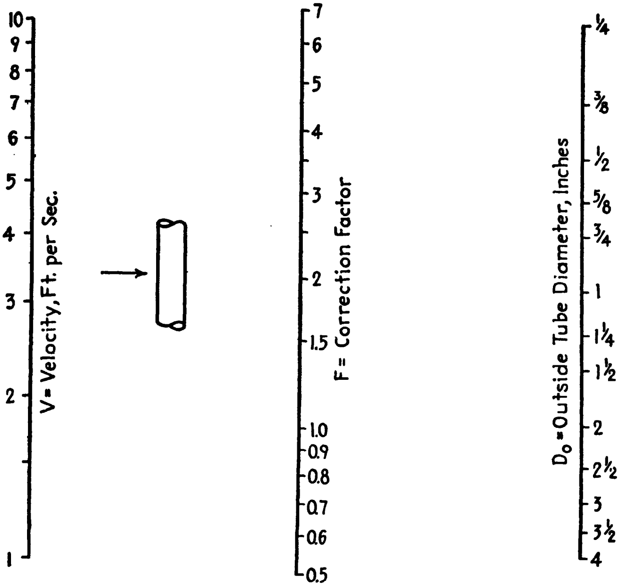

FIG. G-8.—Case 4, correction factors for liquids heated or cooled outside single tubes, direction of flow normal to tube. (*Stoever, Chem. and Met. Eng., May,* 1944.)

TABLE G-10

CASE 5.—BASE FACTORS FOR LIQUIDS HEATED OUTSIDE SINGLE HORIZONTAL TUBES, NATURAL CONVECTION

	Average temperature of the film					
	0°F	50°F	100°F	150°F	200°F	250°F
Acetic acid (100%)	....	....	19.8	18.8	*17.8*	*17.2*
Acetone	....	27.1	28.0	*28.2*	*28.5*	*28.8*
Ammonia	85.5	96.3	108	120	*132*	*144*
Benzene	....	18.4	20.3	21.9	23.5	*25.0*
Carbon disulphide	23.9	24.1	24.6	24.8	*25.1*	*25.3*
Carbon tetrachloride	....	15.7	16.6	16.5	*16.3*	*15.9*
Chlorobenzene	*16.4*	15.5	14.8	14.0	13.4	*13.0*
Ethyl acetate	*23.5*	21.7	20.1	18.5	*17.1*	*15.6*
Ethyl alcohol (100%)	15.6	18.1	20.6	23.1	25.3	*27.4*
Ethyl alcohol (40%)	*17.9*	26.6	36.5	*47.2*	*57.8*	
Ethyl bromide	20.1	20.7	21.1	21.5	*21.7*	*21.9*
Ethyl ether	22.3	23.9	24.8	25.6	*26.4*	*26.9*
Ethyl iodide	*15.9*	17.9	19.8	21.4	23.0	*23.6*
Heptane	*19.4*	20.0	20.4	21.0	*21.5*	*21.9*
Hexane	*18.7*	19.9	21.0	21.8	22.5	*22.9*
Methyl alcohol (100%)	*22.5*	25.2	27.1	*28.7*	*29.8*	*30.9*
Methyl alcohol (90%)	*21.5*	25.9	29.1	*31.8*	*34.1*	*36.4*
Octane (*n*)	*17.0*	18.1	18.5	19.2	*20.0*	*20.5*
Pentane (*n*)	21.9	22.3	22.8	23.3	*24.0*	*24.4*
Sulphur dioxide	37.9	37.2	36.5	36.0	*35.6*	*35.2*
Sulphuric acid (98%)	....	11.8	15.5	*19.2*	*22.9*	
Sulphuric acid (60%)	....	12.5	15.6	18.2	20.3	*21.7*
Toluene	18.1	19.1	20.1	20.9	21.5	*21.7*
Water	....	36.8	47.9	55.0	60.2	*65.0*

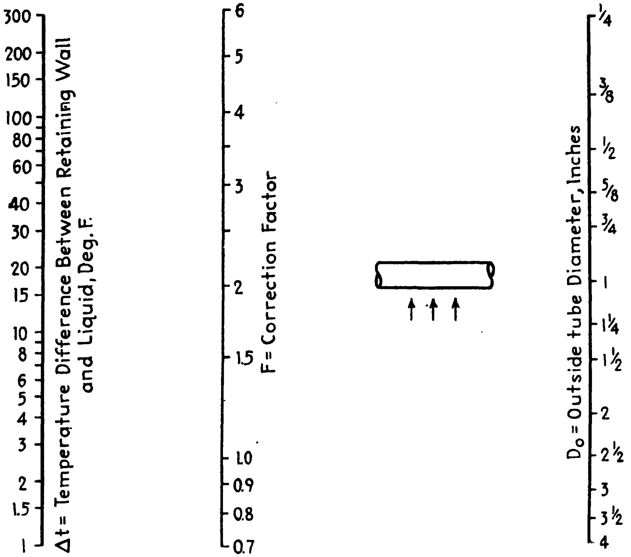

FIG. G-9.—Case 5, correction factors for liquids heated outside single horizontal tubes, natural convection. (*Stoever, Chem. and Met. Eng., May,* 1944.)

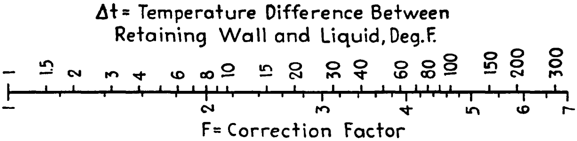

FIG. G-10.—Case 6, correction factor for liquids heated by vertical surfaces, low velocity, or natural convection only. (*Stoever, Chem. and Met. Eng., May,* 1944.)

TABLE G-11

CASE 6.—BASE FACTORS FOR LIQUIDS HEATED INSIDE OR OUTSIDE VERTICAL TUBES OR ON VERTICAL PLATES, LOW VELOCITIES, OR NATURAL CONVECTION ONLY

	Average temperature of the film					
	0°F	50°F	100°F	150°F	200°F	250°F
Acetic acid (100%)	....	....	15.6	15.5	*15.5*	*15.5*
Acetone	*21.0*	22.6	24.1	*24.8*	*25.3*	*25.8*
Ammonia	75.0	88.5	103	118	*136*	*155*
Benzene	....	14.4	16.4	18.2	20.0	*21.7*
Carbon disulphide	19.7	20.3	21.0	21.6	*22.2*	*22.8*
Carbon tetrachloride	*11.4*	12.7	13.8	14.2	*14.4*	*14.8*
Chlorobenzene	*12.0*	12.0	12.0	11.8	11.8	*11.7*
Ethyl acetate	*18.6*	18.1	17.4	16.6	*15.9*	*15.0*
Ethyl alcohol (100%)	10.8	13.2	15.9	18.6	21.2	*23.9*
Ethyl alcohol (40%)	*10.2*	17.4	26.2	*25.1*	*25.4*	
Ethyl bromide	17.1	18.0	18.8	19.4	*19.8*	*20.2*
Ethyl ether	19.4	21.0	22.3	23.4	*24.1*	*24.6*
Ethyl iodide	*12.6*	15.4	17.7	19.8	21.8	*24.0*
Heptane	*14.8*	15.6	16.6	17.2	*18.5*	*19.5*
Hexane	*15.6*	16.7	17.8	18.9	19.4	*19.9*
Methyl alcohol (100%)	*16.7*	19.5	21.9	*23.9*	*25.9*	*27.4*
Methyl alcohol (90%)	*15.1*	19.4	22.6	*25.4*	*27.8*	*30.3*
Octane (*n*)	*12.7*	13.9	14.8	15.8	*16.7*	*17.7*
Pentane (*n*)	18.3	19.3	20.1	20.7	*21.1*	*21.5*
Sulphur dioxide	33.6	33.6	33.6	33.6	*33.6*	*33.6*
Sulphuric acid (98%)	....	7.16	9.43	*11.6*	*13.8*	*15.9*
Sulphuric acid (60%)	....	8.50	11.2	13.3	14.7	*15.3*
Toluene	13.7	14.9	16.1	17.3	18.5	*19.6*
Water	....	23.3	31.9	38.0	42.4	*47.9*

CASE 7.—LIQUIDS HEATED OR COOLED OUTSIDE TUBE BUNDLES, DIRECTION OF FLOW NORMAL TO TUBES

Use data for Case 4 and multiply answer by 1.2 for tubes in line or by 1.3 for staggered tubes. For determining correction factor use velocity at narrowest section between tubes. For baffled heat exchangers, where a small part of the flow is parallel to tubes, use Case 4 data directly, but evaluate correction factor at velocity between tubes at widest part of shell, calculated as

$$\frac{144\,Q}{(d_s - nd)\,l}$$

where Q = rate of flow, cu ft/sec
d_s = inside shell diameter, in.
d = outside tube bundle diameter, in.
n = number of tubes across wide part of shell
l = distance between baffles

CASE 9.—LIQUIDS HEATED OR COOLED INSIDE COILS, TURBULENT FLOW

Use data for Case 1 (heating), or Case 2 (cooling), and multiply answer by 1.2.

CASE 10.—LIQUIDS HEATED OR COOLED OUTSIDE COILS, NATURAL OR FORCED CONVECTION

Use data for Case 4 (forced convection), or Case 5 (natural convection).

d. Equations for Liquids.—The basic equations for film coefficients of fluids recommended by McAdams[1] are given below in dimensional form. Fluids inside tubes or annuli when μ does not exceed 2 or 3 centipoises:

$$h = 18.6 \frac{k^{0.6} c_p^{0.4}}{\mu^{0.4}} \frac{G^{0.8}}{d_e^{0.2}} \qquad \text{(G-13)}$$

Viscous liquids inside tubes or annuli:

$$h = 17.5 \frac{k_f{}^{2/3} c_{pf}{}^{1/3}}{\mu_f{}^{7/15}} \frac{G^{0.8}}{d_e^{0.2}} \qquad \text{(G-14)}$$

Fluids outside tubes:

$$h = 95F_n \frac{k_f{}^{2/3} c_{pf}{}^{1/3}}{\mu_f{}^{4/15}} \frac{G_o^{0.6}}{d_o^{0.4}} \qquad \text{(G-15)}$$

$$= 57F_n \frac{k_f{}^{2/3} c_{pf}{}^{1/3}}{\mu_f{}^{4/15}} \frac{G_c^{0.6}}{d_o^{0.4}} \qquad \text{(G-16)}$$

where h = film coefficient, Btu/(hr)(sq ft)(°F)
k = thermal conductivity of fluid, Btu/(hr)(sq ft)(°F/ft)
μ = viscosity, centipoise
c_p = specific heat, Btu/(lb)(°F)
G = mass velocity, lb/(sec)(sq ft)
d_e = equivalent diameter, in. = inside diameter of circular tube
d_o = outside diameter of circular tube
G_o = true mass velocity across tube at point of closest approach, lb/(sec)(sq ft)
G_c = calculated mass velocity neglecting leakage between baffles (shell and tube exchangers)

$$= \frac{WS}{25BD(S - d_o)}$$

W = flow, lb/hr
S = center-to-center spacing of tubes, in.
B = baffle spacing, in.
D = inside diameter of shell
F_n = factor depending on number of tubes (see Table G-6, p. 241)
= 1 for 10 or more staggered rows
= 0.8 for 10 or more rows in line

NOTE: Subscript f indicates that property should be evaluated at film temperature t_f, which is defined by equation

$$t_f = \frac{t + t_s}{2}$$

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[1] *Op. cit.*

where t = bulk temperature
t_s = surface temperature

The film temperatures used in Eqs. (G-14) to (G-16) present a nuisance in actual computations since they must be found by trial and error. Fortunately, approximate temperatures suffice and, for preliminary work, the relations below may be used for estimation:

Equation	Condition
$t_f = t - \frac{1}{4}\Delta t_m$	Cooling when film coefficients are about equal
$t_f = t - \frac{1}{2}\Delta t_m$	Cooling when film coefficient on other side is much larger
$t_f = t$	Cooling or heating when film coefficient on other side is much smaller
$t_f = t + \frac{1}{4}\Delta t_m$	Heating when film coefficients are about equal
$t_f = t + \frac{1}{2}\Delta t_m$	Heating when film coefficient on other side is much larger

where t_f = average film temperature
t = average bulk temperature
Δt_m = mean temperature difference

Exact estimations of film temperatures will be discussed under over-all heat-transfer coefficients.

In order to use Eqs. (G-13) to (G-16) several properties must be evaluated, making the process somewhat tedious. When this is done for water inside tubes, the results may be expressed more simply[1] as follows:

$$h = 5.6(1 + 0.011t)\frac{G^{0.8}}{d_e^{0.2}} \tag{G-17}$$

where h = film coefficient for water, Btu/(hr)(sq ft)(°F)
t = average temperature, °F
G = mass velocity, lb/(sq ft)(sec)
d_e = equivalent diameter, in.
= inside diameter of circular tube, in.

Table G-12 gives values of $k^{2/3}c_p^{1/3}$ for petroleum products for use in Eqs. (G-14) to (G-16).

For open ("trombone," trickle) coolers for cooling fluids flowing through single horizontal tubes or tube bundles by trickling water flow over the pipes, the following equation[1] gives the film coefficient to about ±25 per cent:

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[1] McAdams, *op. cit.*

$$h = 940 \sqrt{\frac{m}{d_o L}}$$

where m = gallons of water per minute flowing over a tube, L ft long, d_o in. outside diameter

h = film coefficient, Btu/(hr)(sq ft)(°F)

TABLE G-12.—COMBINED THERMAL CONDUCTIVITY, SPECIFIC HEAT FACTORS OF PETROLEUM PRODUCTS FOR USE IN EQS. (G-14) TO (G-16)
(Based on data of Cragoe, *Nat. Bur. Standards, Misc. Pub.* 97)

Density of hydrocarbon		Temperature range, °F	Factor $k^{2/3}c_p^{1/3}$ where k = thermal conductivity, Btu/(hr)(sq ft)(°F/ft) c_p = specific heat, Btu/(lb)(°F)
°A.P.I.	Specific gravity (60/60)		
10	1.0000	0–800	0.12
20	0.9340	0–800	0.13
30	0.8762	0–800	0.14
40	0.8251	0–600	0.14–0.15
50	0.7796	0–400	0.15–0.16
60	0.7389	0–400	0.16

e. Condensing Vapors.—The rate of transfer of heat to cold surfaces depends on whether the condensation is of the film type or dropwise type. The names are descriptive of the mechanisms. Dropwise condensation of steam frequently occurs on polished surfaces and is promoted by addition of oil or other organic substances which prevent complete wetting of the surface by water. Although dropwise coefficients are higher, film-type condensation is more common in practice and will alone be considered here. The original equations for rate of condensation were derived by Nusselt in 1916 under the following assumptions:

1. Heat-transfer rate is determined solely by the rate of transfer through condensed liquid film
2. This condensed liquid film is continuous
3. Flow of film results from the effect of gravity alone
4. Flow of film is streamline

The recommended equations given below[1] are based largely on the original derivation. These equations are valid unless the liquid flow

[1] McAdams, *op. cit.*

is so heavy that turbulent flow results.[1] If this occurs, higher heat transfer results, so that the equations are safe.

Outside vertical tubes:

$$h = 129\left(\frac{k^3\rho^2\Delta H}{\mu L \Delta t}\right)^{1/4} \tag{G-18}$$

Outside a vertical tier of horizontal tubes:

$$h = 154\left(\frac{k^3\rho^2\Delta H}{\mu N d_0 \Delta t}\right)^{1/4} \tag{G-19}$$

where h = film coefficient, Btu/(hr)(sq ft)(°F)
k = thermal conductivity of condensed liquid (at temperature of cold surface), Btu/(hr)(sq ft)(°F/ft)
ρ = density of liquid at cold surface temperature, lb/cu ft
ΔH = latent heat of vaporization at condenser pressure, Btu/lb
μ = viscosity of liquid at cold surface temperature, centipoise
L = length of vertical tubes, ft
N = number of rows of tubes in a vertical tier
d_o = outside pipe diameter, in.
Δt = difference in temperature between vapor and cold surface

Figure G-11 and Table G-13 permit the estimation of film coefficients for the condensation of 18 vapors on horizontal tubes. Figure G-12 gives the film coefficients for 17 vapors on a horizontal tube 1.9 in. outside diameter. Rates of condensation of vapor mixtures are usually intermediate between the rates of the component vapors; to be safe, the lowest film coefficient of any component may be assumed for the mixture.

For vapor mixtures that form immiscible condensates, a partial dropwise condensation probably results. Data of Baker and coworkers[2] indicate that film coefficients over 400 Btu/(hr)(sq ft)(°F) are usually obtainable for condensation of steam and organic vapors to form a two-phase condensate.

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[1] Turbulent flow begins, approximately, when

$$\frac{W}{N_v d\mu} = 300 \text{ (vertical tubes)} \qquad \frac{W}{N_H L\mu} = 2{,}500 \text{ (horizontal tubes)}$$

where W = lb condensate/hr
N_v = number of vertical tubes
d = diameter of vertical tube, in.
μ = viscosity, centipoise
N_H = number of horizontal rows of horizontal tubes
L = length of tubes, ft

[2] Baker and Tsao, *Trans. Am. Inst. Chem. Engrs.*, **36**, 517 (1940). Baker and Mueller, *Ind. Eng. Chem.*, **29**, 1067 (1937). (Vapors studied: benzene, toluene, heptane, chlorobenzene, and trichloroethylene.)

TABLE G-13.—BASE FACTORS FOR CONDENSATION OF PURE SATURATED VAPORS ON HORIZONTAL TUBES (Stoever, *Chem. & Met. Eng.*, May, 1944, p. 98)

	Temperature of condensate film (assume equal to tube wall)					
	50°F	100°F	150°F	200°F	250°F	300°F
Acetic acid	.....	511	495	470	424	373
Acetone	772	789	805	805	795	780
Ammonia	2,768	3,145	3,459	3,711	*3,875*	*3,965*
Aniline	*275*	405	544	685	830	977
Benzene	554	609	658	706	755	798
Carbon disulphide	924	933	933	924	905	868
Carbon tetrachloride	551	580	569	*482*		
Chloroform	735	791	847	*895*	*950*	*997*
Ethyl acetate	*702*	772	835	889	936	990
Ethyl alcohol	*495*	556	618	678	745	807
Ethyl ether	620	646	665	678	691	705
Heptane	*488*	537	580	607	628	645
Hexane	*525*	552	576	592	608	614
Methyl alcohol	695	772	850	920	972	103
Octane	*482*	513	538	554	575	585
Propyl alcohol (*iso*)	*284*	400	488	548	*596*	*632*
Steam	1,830	2,440	3,020	3,590	4,120	4,660
Sulphur dioxide	1,260	1,200	1,115	1,010	*900*	*780*

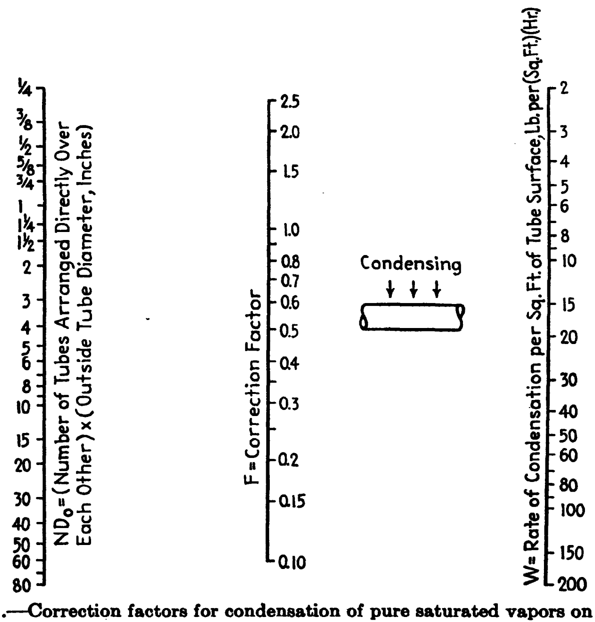

FIG. G-11.—Correction factors for condensation of pure saturated vapors on horizontal tubes. (*Stoever, Chem. & Met. Eng., May,* 1944.)

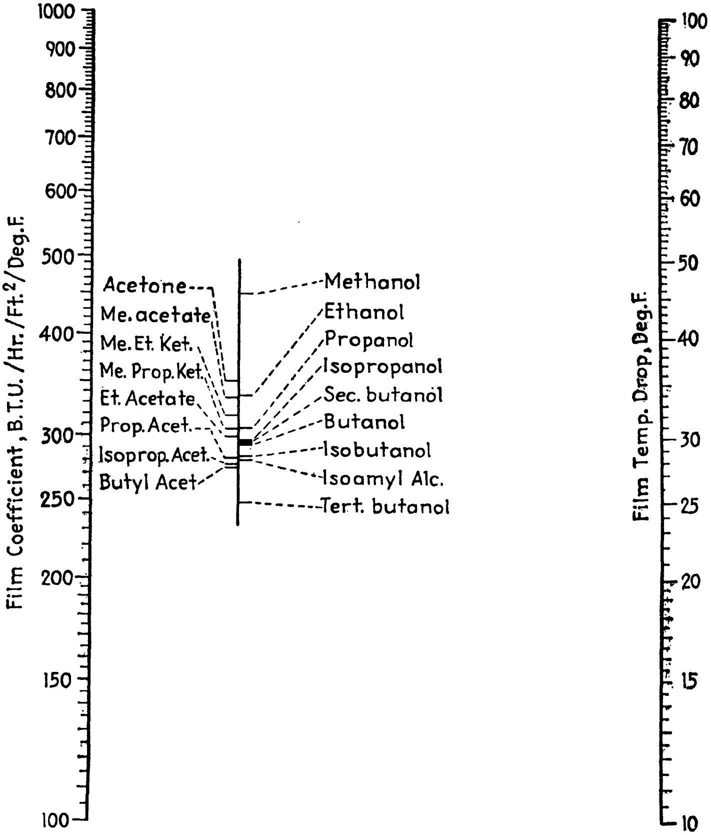

FIG. G-12.—Film coefficients of condensing alcohols, ketones, and esters on 1.9-in. tube. [*Reprinted from Othmer and Berman, Ind. Eng. Chem.* **35**, 1068, (1943); *by permission of the American Chemical Society.*]

f. Boiling Liquids.—The rate of evaporation of a liquid depends on the turbulence produced by boiling. As a result, the film coefficient is increased at higher boiling rates and, therefore, increases rapidly with the temperature difference supplied. This increase in rate does not, however, continue indefinitely but reaches a maximum rate which is about 150 to 600 lb/(hr)(sq ft) at atmospheric pressure. At higher pressures the maximum boiling rates are higher. The temperature difference between the surface and the boiling liquid at this maximum flux ranges between 40 and 80°F at atmospheric pressure, but may be as low as 5°F at high pressures. The factors involved in heat transfer to boiling liquids are not well understood and experimental data are frequently contradictory. However, Cichelli and Bonilla[1] have succeeded in correlating the maximum boiling rates. They also discuss a number of equations that have had some measure of success in predicting film coefficients. It is felt that none of these can be recommended for general usage without a more detailed discussion of the ranges of validity than would be appropriate here.

In any event, basing design directly on experimental over-all coefficients is strongly recommended, if close design is important. The section that follows gives a few over-all coefficients involving boiling liquids. Fortunately, the coefficients are high so that the arbitrary installation of excess surface may not be costly. Further, the film coefficient of the other fluid is often much lower and largely determines the surface requirement.

5. Over-all Heat Transfer

a. Heat-transfer Equipment.—The shell and tube exchangers are in very common usage for industrial heat transfer. Their design involves a careful balance between a large number of factors,[2] the most important of which is securing the maximum velocities with available pressure drops. On the tube side this is effected by relation of tube diameter to total length. If a long path is essential to secure the velocity and area in reasonable sized tubes, several passes or multiple units may be required. The mean temperature difference is usually reduced by more than one pass in a single shell. On the shell side, the velocity may be adjusted by tube and baffle spacing, or occasionally by more than one shell pass.

Appreciation of these factors is important to design of the process prior to equipment specification. When the temperature changes on both fluids are large, the problem of securing proper velocities is likely to be more severe than if the temperature changes are small. In some cases it is economic to use more cooling water with a smaller temperature rise. This favors increased water velocities, and multipass arrangements.

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[1] *Trans. Am. Inst. Chem. Engrs.*, **41**, 755 (1945).

[2] Baylock, *Trans. Am. Inst. Chem. Engrs.*, **40**, 593 (1944) gives an excellent brief discussion.

Double pipe exchangers are the easiest to design and are frequently employed where a small amount of heat is to be transferred, as in the case of a pilot plant. Where the film coefficient on one side is much greater than on the other, increased area on the side of low rate is an advantage. Finned tubes are frequently used to accomplish this as in the case of air heaters. Fins may be either around the tube for cross flow, or along the length for parallel flow. In the oil industry, open or "trombone" coolers are fairly common. In these, cooling is effected by spraying water over a tube bundle. Such coolers are inexpensive but require a larger area. In addition, there are submerged coils, steam jackets, and many other devices for heat transfer.[1]

Cooling water towers and contact coolers are used for heat transfer but present an entirely different type of problem and are treated briefly in Chapter M on Water.

Tube bundles are usually made by expanding the tubes into tube sheets. Table G-14 gives minimum center-to-center spacing for this type of construction.

TABLE G-14.—MINIMUM CENTER-TO-CENTER SPACING FOR TUBES EXPANDED IN TUBE SHEET

[Blaylock, *Trans. Am. Inst. Chem. Engrs.* **40**, 593 (1944)]

Outside tube diameter, in.	5/8	3/4	1	1¼
Triangular spacing, in.	13/16	15/16	1¼	19/16
Rectangular spacing, in.	7/8	1	1¼	19/16

The diameter of the shell depends on the number and arrangement of tubes in addition to the center-to-center spacing. Table G-15 gives data on various numbers of tubes arranged in a hexagonal pattern (either around a central tube, or starting with three tubes grouped around the center). Table G-16 gives data on rectangular spacing. For a large number of tubes, the shell diameter may be approximately estimated by the equations below:

Rectangular arrangement:

$$D = 1.25d\sqrt{n}$$

Hexagonal arrangement:

$$D = 1.15d\sqrt{n}$$

---

[1] Schwarz, *Chem. & Met. Eng.*, May, 1944, p. 120.

where D = shell diameter, in.
d = center-to-center tube spacing, in.
n = number of tubes

It will be noted that the hexagonal arrangement of tubes is the more economical of space and, therefore, affords higher shell velocities. However, the rectangular array is frequently used because cleaning of the tubes is considerably easier.

TABLE G-15.—DIAMETER RATIOS FOR TUBES ARRANGED HEXAGONALLY IN SHELLS
(Deutsch, *Chem. & Met. Eng.*, August, 1940, p. 538)

No. of tubes	Ratio: $\frac{\text{shell diameter}}{\text{center-to-center spacing}}$	No. of tubes	Ratio: $\frac{\text{shell diameter}}{\text{center-to-center spacing}}$
3	2.15	61	9.00
7	3.00	63	9.09
12	4.05	69	9.33
13	4.46	73	9.77
19	5.00	85	10.16
27	6.03	90	10.86
31	6.28	96	11.06
37	7.00	102	11.26
42	7.43	109	11.58
48	8.02	114	12.01
55	8.21	121	12.14

TABLE G-16.—DIAMETER RATIOS FOR TUBES ARRANGED RECTANGULARLY IN SHELLS

No. of Tubes	Ratio: $\frac{\text{Shell diameter}}{\text{Center-to-center spacing}}$
4	2.41
5	3.00
8	4.00
12	4.44
13	5.00
16	5.3
22	6.2
29	7.05
37	7.6

b. Mean Temperature Difference.—The over-all transfer of heat is usually computed as the product of three quantities: the surface area, the mean temperature difference, and the over-all coefficient of heat transfer. This obviates the need for integration over the entire surface. Actually the mean temperature difference is derived by such

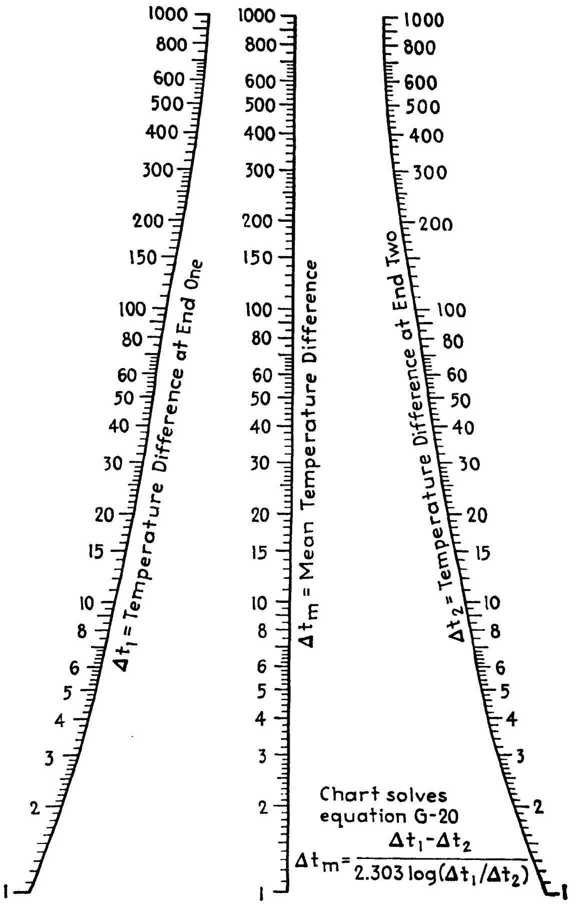


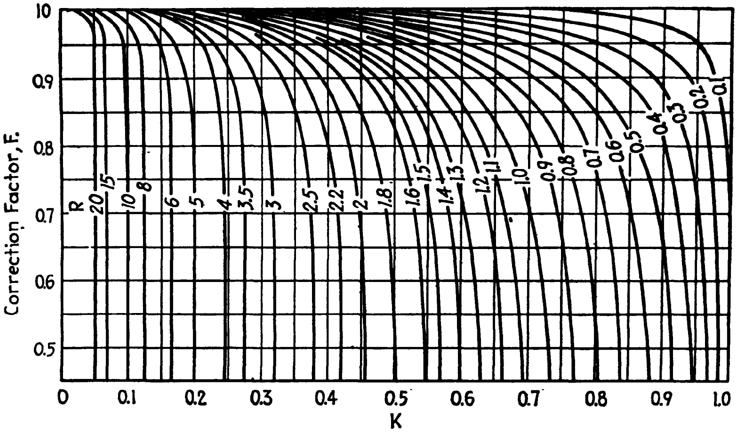
FIG. G-13.—Logarithmic temperature differences.

an integration under the assumptions that the over-all coefficient of heat transfer is constant and that any variation in temperature of the fluids is linear with respect to the heat absorbed or lost. These conditions are seldom accurately fulfilled, but the error is not often serious. The results of this integration for single-pass exchangers (either cocurrent or countercurrent) may be most conveniently expressed as the integrated average effect of the temperature gradient between the two fluids. This turns out to be the logarithmic mean temperature difference, which is given by Eq. (G-20) or in graphical form by Fig. G-13.

$$\Delta t_m = \frac{\Delta t_1 - \Delta t_2}{2.303 \log \dfrac{\Delta t_1}{\Delta t_2}} \qquad \text{(G-20)}$$

where Δt_m = mean temperature difference
Δt_1 = largest temperature difference
Δt_2 = smallest temperature difference

The same integration may be performed for multipass exchangers, but the results are algebraically complicated and are usually expressed in graphical form as a factor for correction of the logarithmic mean temperature difference. Figure G-14 is such a chart for exchangers with four or more tube passes and two shell passes. Where the tube and shell passes are the same in number and flow relations, no correction factor is needed. Also if one side or the other of the exchanger is at constant temperature (as in the case of condensing steam, etc.), no correction factor need be used for the number of passes.



$$K = \frac{t_2 - t_1}{T_1 - t_1}; \quad R = \frac{T_1 - T_2}{t_2 - t_1}$$

T_1 = Inlet temperature, Shell side t_1 = Inlet temperature, Tube side
T_2 = Outlet temperature, Shell side t_2 = Outlet temperature, Tube side

FIG. G-14.—Mean-temperature-difference correction factors; two shell passes, four or more tube passes. (*Reprinted from Standards of Tubular Exchanger Manufacturers Association*, 1941.)

A word of caution should, perhaps, be added. When one of the two fluids is partly, but not totally, evaporated or condensed, the true mean temperature difference may be quite different from what would be computed by the methods just discussed. In this case, the smallest temperature difference may occur even in the middle of the exchanger.

c. Over-all Coefficients.—The flow of heat is analogous to that of electricity. In both cases, parallel conductivities are additive, series resistances are additive. In heat flow, however, we are used to thinking in terms of conductivity rather than resistance, its reciprocal. Adding up the resistances in series, we obtain

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{d_o}{d_i}\frac{1}{h_i} + f_o + \frac{d_o}{d_i}f_i + \frac{d_o}{d_m}\frac{L}{k} \tag{G-21}$$

$$\frac{1}{U_i} = \frac{1}{h_i} + \frac{d_i}{d_o}\frac{1}{h_o} + f_i + \frac{d_i}{d_o}f_o + \frac{d_i}{d_m}\frac{L}{k} \tag{G-22}$$

$$\frac{1}{U_f} = \frac{1}{h_i} + \frac{1}{h_o} \tag{G-23}$$

where U_o = over-all coefficient of heat transfer based on outside surface of tubes, Btu/(hr)(sq ft)(°F)

U_i = over-all coefficient of heat transfer based on inside area of tubes, Btu/(hr)(sq ft)(°F)

U_f = over-all coefficient of heat transfer computed from film coefficients alone, neglecting metal resistance, fouling resistance, and area ratio, Btu/(hr)(sq ft)(°F)

h_o = film coefficient, outside of tube, Btu/(hr)(sq ft)(°F)

h_i = film coefficient, inside of tube, Btu/(hr)(sq ft)(°F)

f_o = fouling factor outside of tube (see Table G-17)

f_i = fouling factor inside of tube (see Table G-17)

d_o = outside diameter of tube, in.

d_i = inside diameter of tube, in.

d_m = logarithmic mean of d_o and d_i, in.,

$\left(\text{usually factors } \frac{d_i}{d_m} \text{ or } \frac{d_o}{d_m} \text{ may be neglected}\right)$

L = thickness of tube wall, ft

k = thermal conductivity of tube wall, Btu/(hr)(sq ft)(°F/ft)

For preliminary calculations the simpler Eq. (G-23) may be used; for close design, the inclusion of metal resistance and fouling factors is desirable. These equations presume that the various resistances involved are independent of the temperature differences. In some cases, such as condensing vapors and boiling liquids, the film coefficient depends on the temperature difference. Consequently these temperatures must be assumed and checked by subsequent calculation. For steady operation, the heat passes through the successive layers at the same rate. Expressing this algebraically,

$$U_o\Delta t_m = h_o\Delta t_o = h_i\frac{d_o}{d_i}\Delta t_i, \text{ etc.} \tag{G-24}$$

where U_o = over-all coefficient based on outside tube area, Btu/(hr)(sq ft)(°F)
Δt_m = mean temperature difference, °F
h_o = film coefficient outside of tube, Btu/(hr)(sq ft)(°F)
h_i = film coefficient inside of tube, Btu/(hr)(sq ft)(°F)
d_i, d_o = diameter of tube, in.; inside, outside.
Δt_0 = mean temperature difference between shell fluid and outside of wall, °F
Δt_i = mean temperature difference between tube fluid and inside of wall, °F

Equation (G-24) permits the estimation of the mean temperature differences and, therefore, a check on the assumptions originally made in computing the film coefficients.

TABLE G-17.—FOULING RESISTANCES
(Based on Standards of Tubular Exchanger Manufacturers Association 1941)
[See Eqs. (G-21) and (G-22)]

Fuel oil	0.005
Crude oil	0.002–0.007
Clean circulating oil	0.001
Machinery and transformer oil	0.001
Quenching oil	0.004
Vegetable oils	0.003
Manufactured gas	0.01
Organic vapors	0.0005
Clean steam	0.0
Exhaust steam (oil bearing)	0.001
Alcohol vapors	0.0
Refrigerating vapors (condensing from reciprocating compressors)	0.002
Air	0.002
Organic liquids	0.001
Refrigerating liquids	0.001
Brine (cooling)	0.001
Sea water:	
0–240°F	0.0005
240–400°F	0.001
Brackish water	0.001–0.003
Cooling-tower water:	
Treated, 0–240°F	0.001
Treated, 240–400°F	0.002
Untreated	0.003–0.005
City or well water:	
0–240°F	0.001
240–400°F	0.002
River	0.002–0.004
Hard (over 15 grains/gal)	0.003–0.005
Distilled	0.0005
Treated boiler feed	0.001

The accuracy of heat-transfer calculations may be fairly high under favorable conditions. Usually accuracy suffers somewhat from uncertainties in basic physical data, in equations, and in approximations used. Consequently rather large factors of safety are advised, and over-all coefficients of 30 to 90 per cent of calculated values should be used in final design. Tables G-18 to G-22 give typical over-all coefficients of heat transfer.

Table G-18.—Over-all Heat-transfer Coefficients for Evaporation of Water by Submerged Copper Coil (Claassen)
(McAdams, "Heat Transmission," 2d ed., McGraw-Hill Book Company, Inc., New York, 1942)
U = Btu/(hr)(sq ft)(°F)

	Δt_o, °F							
	20	30	40	50	60	70	80	90
U for 212°F	390	490	560					
U for 187°F	...	360	440	520	600			
U for 158°F	...	...	...	...	510	600	660	720

Table G-19.—Over-all Heat-transfer Coefficients for Evaporation of Water by a Submerged Coil at Atmospheric Pressure (Claassen)
(McAdams, "Heat Transmission," 2d ed., McGraw-Hill Book Company, Inc., New York, 1942)
U = Btu/(hr)(sq ft)(°F)

	Weight, % solids							
	0	10	20	30	40	50	60	70
U, salt solutions, $\Delta t_o = 18$°F	420	430	440					
U, molasses, $\Delta t_o = 12$°F	360	350	340	320	290	250	210	170

Table G-20.—Over-all Coefficients of Heat Transfer for Condensing Steam to Boiling Water at 167°F in a Submerged-tube Evaporator
(McAdams, "Heat Transmission," 2d ed., McGraw-Hill Book Company, Inc., New York, 1942)
U = Btu/(hr)(sq ft)(°F)

	Δt_o, over-all Δt, °F				
	18	27	36	45	54
U_o, rusty iron	280	300	325	350	375
U_o, clean iron	300	385	460	535	610
U_o, slightly dirty copper	580	780	950	1120	
U_o, polished copper	820	1110	1470	1810	2120

TABLE G-21.—ORDINARY RANGES OF OVER-ALL COEFFICIENTS
(Under many conditions higher or lower values may be realized.)
(Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York, 1941)
U = Btu/(hr)(sq ft)(°F)

Type of heat exchanger	State of controlling resistance		Typical fluid	Typical apparatus
	Free convection, U	Forced convection, U		
Liquid to liquid	25– 60	150–300	Water	Liquid-to-liquid heat exchangers
Liquid to liquid	5– 10	20– 50	Oil	
Liquid to gas*	1– 3	2– 10	....	Hot-water radiators
Liquid to boiling liquid	20– 60	50–150	Water	Brine coolers
Liquid to boiling liquid	5– 20	25– 60	Oil	
Gas* to liquid	1– 3	2– 10	....	Air coolers, economizers
Gas* to gas	0.6– 2	2– 6	....	Steam superheaters
Gas* to boiling liquid	1– 3	2– 10	....	Steam boilers
Condensing vapor to liquid	50–200	150–800	Steam to water	Liquid heaters and condensers
Condensing vapor to liquid	10– 30	20– 60	Steam to oil	
Condensing vapor to liquid	40– 80	60–150	Organic vapor to water	
Condensing vapor to liquid	....	15–300	Steam-gas mixture	
Condensing vapor to gas*	1– 2	2– 10	....	Steam pipes in air, air heaters
Condensing vapor to boiling liquid	40–100	....	....	Scale-forming evaporators
Condensing vapor to boiling liquid	300–800	....	Steam to water	
Condensing vapor to boiling liquid	50–150	....	Steam to oil	

* At atmospheric pressure.

TABLE G-22.—OVER-ALL COEFFICIENTS OF HEAT TRANSFER FROM CONDENSING STEAM TO BOILING WATER IN A BASKET EVAPORATOR. 31 STEEL TUBES 1 IN. OUTSIDE DIAMETER AND 4 FT LONG

(McAdams, "Heat Transmission," 2d ed., McGraw-Hill Book Company, Inc., New York, 1942)

U = Btu/(hr)(sq ft)(°F)

	Δt_o, °F					
	10	20	30	40	50	60
U for 140°F	120	205	270	320	350	370
U for 167°F	220	320	400	440	480	500
U for 212°F	320	440	500	520		

d. Illustrative Example. Make a preliminary design of a cooler handling 20 gpm of ethyl acetate to be cooled from 170 to 80°F by 70°F cooling water. A 20°F rise on the water may be assumed. The cooler is to be of the shell and tube type constructed with brass tubes.

SOLUTION:

A. Process Data:

1. Physical properties, ethyl acetate,
   Specific heat at 125°F (52 + °C) = 0.47 Btu/(lb)(°F) (Fig. E-15)
   Density at 60°F 7.6 lb/gal (Fig. D-3)
   Density at 125°F 7.2 lb/gal (Fig. D-3)
2. Flow of ethyl acetate, 20 gpm (measured at 60°F), $20 \times \frac{7.6}{7.2} = 21.1$ gpm measured at the mean temperature of 125°F, $20 \times 7.6 \times 60 = 9{,}120$ lb/hr
3. Heat load = $Q = 9{,}120 \times (170 - 80) \times 0.47 = 386{,}000$ Btu/hr
4. Water flow, 1 lb/hr will remove 20 Btu/hr and flow $= \frac{386{,}000}{20} = 19{,}300$ lb/hr or $\frac{19{,}300}{500} = 38.6$ gpm (1 gpm = 500 lb/hr)

B. Mean Temperature Difference:

Temperature difference at cold end = 80 − 70 = 10°F

Temperature difference at hot end = 170 − 90 = 80°F

Mean temperature difference (single pass) = 34°F (Fig. G-13)

Estimated film temperature of ethyl acetate, 125 − ¼ 34 = 116.5, say 115°F

Estimated film temperature of water, 80 + ¼ 34 = 88.5°, say 90°F

C. Tube Side:

1. Assume water flows through 27 tubes, each, ¾ in. OD × 16 B.W.G. (27 is a preferred number for hexagonal spacing)
2. Tube data (from Table F-20),
   Outside diameter = ¾ in.
   Wall thickness, 16 B.W.G. = 0.065 in.
   Inside diameter = 0.620 in.
   Circumference, outside = 0.1963 ft
   Circumference, inside = 0.1623 ft
   Velocity = 1.061 fps for flow of 1 gpm
3. Velocity = 38.6 × 1.06/27 = 1.51 fps
4. Film coefficient,
   Base factor at 50°F = 225 (Table G-7)
   at 100°F = 322
   at 90°F = 300 (interpolation)
   Correction factor at 1.51 fps, 0.62 in. = 1.5 (Fig. G-5)
   Film coefficient = 1.5 × 300 = 450 Btu/(hr)(sq ft)(°F)

D. Shell Side:

1. Minimum tube spacing, center to center, for ¾ in. OD tubing = $^{15}/_{16}$ in. (Table G-14)
2. Minimum shell diameter,
   6.03 × (center-to-center spacing) (Table G-15)
   6.03 × $^{15}/_{16}$ = 5.66 in.
3. Use 6-in., schedule 40, pipe for shell,
   Inside diameter = 6.065 in. (Table F-19)
   Actual center-to-center spacing = $\frac{6.065}{6.03}$ or 1 in.
4. Number of tubes in line must be six since shell is just over six times center-to-center spacing. This may be checked by layout (beginning with three tubes grouped as around central point)
5. Velocity, u, fps = $\frac{144Q}{(d_s - nd)L}$
   where Q = cu ft/sec = $\frac{21.1}{7.48 \times 60} = 0.047$
   $d_s = 6.065$ in.
   $nd = 6 \times ¾ = 4.5$ in.
   L = baffle spacing, in.
   $$u = \frac{144 \times 0.047}{(6.065 - 4.5)L} = \frac{4.32}{L}$$
   This suggests 4-in. baffles to give $u = 1.08$ fps
6. Film coefficient,
   Base factor at 100°F = 137 (Table G-9)
   at 150°F = 129
   at 115°F = 135 (interpolated)
   Correction factor at 1.08 fps and ¾ in. = 1.2 (Fig. G-8)
   Film coefficient, 1.2 × 135 = 162 Btu/(hr)(sq ft)(°F)

E. Over-all Coefficient Based on Outside Surface of Tubes:

[By Eq. (G-21)]

$$\frac{1}{h_o} = \frac{1}{162} \cdots\cdots \quad 0.0062$$

$$\frac{d_o}{d_i}\frac{1}{h_i} = \frac{0.75}{0.62 \times 450} \cdots\cdots \quad 0.0027$$

$$f_o \cdots\cdots \quad 0.0010 \text{ (Table G-17)}$$

$$\frac{d_o}{d_i} f_i = \frac{0.75}{0.62} 0.002 \cdots\cdots \quad 0.0024 \text{ (Table G-17)}$$

$$\frac{d_o}{d_m}\frac{L}{k} = \frac{0.75}{0.68}\frac{0.065}{12 \times 58} \cdots\cdots \quad 0.0001 \text{ (}k\text{ from Table G-4)}$$

$$\frac{1}{U_o} = \text{sum} \cdots\cdots \quad 0\ 0124$$

$$U_o = 80 \text{ Btu/(hr)(sq ft)(°F)}$$

F. Length of Tubes and Shell:

1. Area required, $\frac{\text{heat transferred}}{\text{over-all coefficient} \times \text{mean temperature difference}}$,

$$\frac{386{,}000}{80 \times 34} = 142 \text{ sq ft}$$

2. Length, $\frac{\text{area}}{\text{perimeter} \times \text{number of tubes}}$, $\frac{142}{0.1963 \times 27} = 27$ ft

Therefore, two units are required, each 14 ft long.

G. Check on Film Temperatures Assumed:

1. Ethyl acetate,

$Q = h_o A_o \Delta t$

$386{,}000 = 162 \times 142\Delta t$

$\Delta t = 16.7°\text{F}$

Film temperature = $125 - \frac{1}{2} \times 16.7 = 117°\text{F}$.

Assumed = 115°F, hence error is small.

2. Water,

$Q = h_i A_i \Delta t$

$$386{,}000 = (450)(142)\frac{0.62}{0.75}\Delta t$$

$\Delta t = 5°\text{F}$

Film temperature = $80 + \frac{1}{2} \times 5 = 82.5°\text{F}$.

Assumed 90°F, hence error is small.

Discussion: Though only one set of calculations is shown, two earlier assumptions were made and quickly discarded. A two-unit exchanger designed, as indicated, would probably give performance reasonably close to that desired. However, the design is not wholly satisfactory. The baffle spacing is undesirably close, and the length of 27 ft is longer than desirable, because two units are required even though no factor of safety is allowed. If more tubes are assumed and a larger baffle spacing is taken to overcome these difficulties, the lowered velocities will result in a lower over-all coefficient, so that a great many more would be needed. Incidentally, at these lower velocities the charts cannot be used and equations such as (G-13) and (G-16) would have to be employed. If the velocity is too low in the tubes, turbulent flow will not be obtained (see Chapter F). The use of smaller tubes would make it easier to design a single exchanger of suitable length. Less difficulty in securing suitable velocities would result by using the ethyl acetate as the tube fluid with two or more tube passes. In order to secure a good temperature difference with this arrangement, a smaller temperature rise would have to be taken on the water. A double-pipe exchanger could be used with some advantage for this application.

In short, the solution found is no more than the problem requested: a preliminary design of equipment which would do the job and which should afford a starting point for a more refined final design. The problem is presented in this status in the belief that it illustrates the principles better than would a final solution. Experts on the design of exchangers are able to diagnose such situations quickly from a backlog of experience gained by repeated calculations of this type.

6. Heat Losses by Open Equipment

Bare surfaces lose heat by radiation and convection. Radiation has already been treated earlier in the chapter. The heat loss by

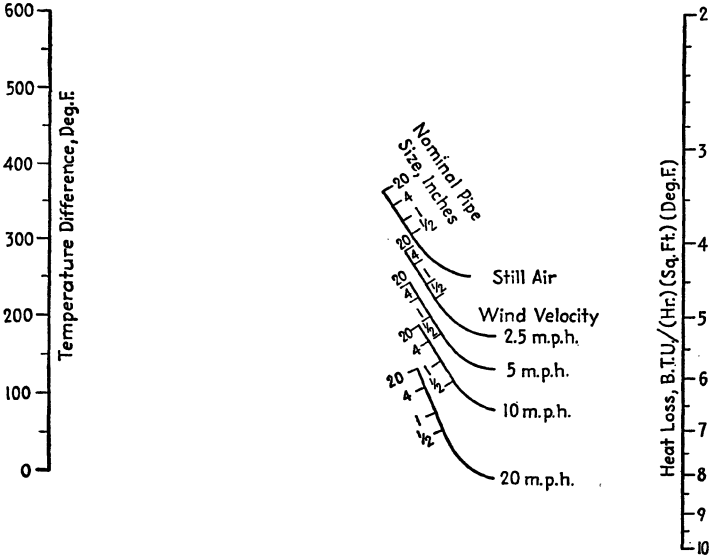


FIG. G-15.—Heat losses from bare iron pipe. *(Based on data from "Heat Insulation Handbook," Ehret Magnesia Manufacturing Company, Valley Forge, Pa., 1942.)*

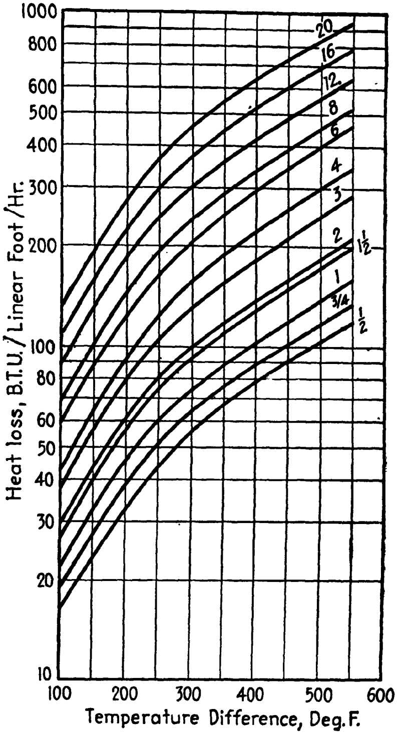


FIG. G-16.—Heat losses from pipe insulated with standard 85 per cent magnesia.

natural convection in absence of any wind, *i.e.*, to still air, may be estimated by the equations given below.[1]

Top-surface horizontal plates...... $h = 0.38(\Delta t)^{0.25}$
Bottom-surface horizontal plates... $h = 0.2(\Delta t)^{0.25}$
Vertical plates (over 1 ft high)...... $h = 0.27(\Delta t)^{0.25}$
Piping........................ $h = 0.27(\Delta t/D_o)^{0.25}$

where h = film coefficient, Btu/(hr)(sq ft)(°F)
Δt = temperature difference, °F
D_o = outside diameter, ft.

It is more convenient for most purposes to lump the radiant and convection transfers together. Figure G-15 gives such data on losses by bare pipe. It should be remembered that rates in rainy weather will be much larger. Similar values for insulated pipe are given in

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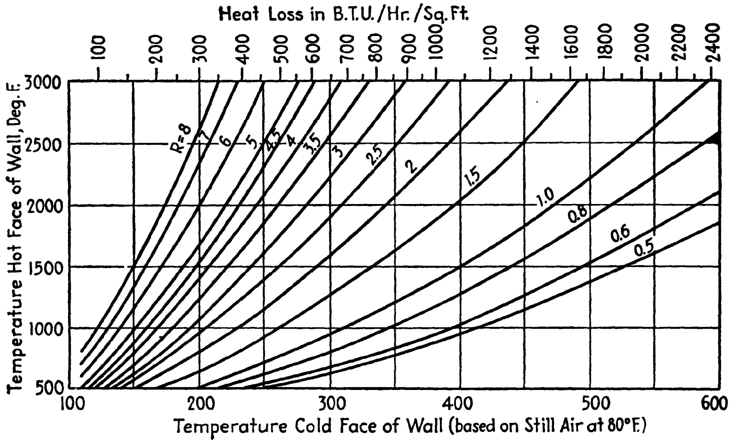
[1] McAdams, *op. cit.*

Fig. G-16. The loss from large flat surfaces is about 0.20 Btu/(hr)(sq ft)(°F) when insulated with 2 in. of rock wool or about 0.24 Btu/(hr)(sq ft)(°F) when insulated with 2 in. of 85 per cent magnesia.



Temperature at first joint from hot face = hot face temperature $-\left(\frac{\text{Btu loss} \times L_1}{K_1}\right)$

Temperature at second joint from hot face = first joint temperature $-\left(\frac{\text{Btu loss} \times L_2}{K_2}\right)$

For a one-component wall $R = \frac{L}{K}$ where L = thickness of wall in inches

K = conductivity (Btu/sq ft/deg F difference in temperature across 1 in. thickness)

For a wall of n components, $R = \frac{L_1}{K_1} + \frac{L_2}{K_2} + \cdots + \frac{L_n}{K_n}$

where L_1, L_2, etc. = thickness of each component

K_1, K_2, etc. = conductivity of each component

Fig. G-17.—Heat losses through furnace walls to still air. (*Copyright by The Atlas Lumnite Cement Company. Reproduced by their permission.*)

Figure G-17 permits estimation of heat losses from furnace walls. This chart is based on still air at 80°F. Wind increases these somewhat and lowers the temperature of the cold faces considerably.

CHAPTER H

COMBUSTION

By all odds the most important source of energy for processing is the combustion of fuels with air. This chapter gives data on air and specific fuels. The last section is intended to centralize data common to all fuels, though some of the charts therein are based on specific fuels. Although combustion equipment is treated very briefly, an effort has been made to mention factors of importance in the choice of fuels and for estimating utility requirements of combustion processes.

Several of the many excellent texts on fuel and combustion are listed below. Information is frequently given in works primarily devoted to other subjects, notably thermodynamics and power.

Haslam and Russell, "Fuels and Their Combustion," McGraw-Hill Book Company, Inc., New York, 1926.
Moore, "Coal," John Wiley & Sons, Inc., New York, 1940.
Moore, "Liquid Fuels," The Technical Press, Ltd., London, 1935.
"Combustion," 3d ed., American Gas Association, New York, 1932.
Trinks, "Industrial Furnaces," 2 vols., John Wiley & Sons, Inc., New York, 1942.
Dunstan, "Science of Petroleum," 4 vols., Oxford Press, England, 1938.

1. Composition of Air

The composition of air is, fortunately, very constant. The only appreciable variation arises from local contamination, and even this is seldom sufficient to affect combustion processes. Noyes and Sherrill[1] give the composition of pure dry air as follows:

	Mole per Cent
Oxygen (O_2)	21.0
Nitrogen (N_2)	78.0
Argon (A)	0.94
Carbon dioxide (CO_2)	0.03
Other (Ne Kr, etc.)	0.03

Since argon and other rare gases are normally reported as nitrogen in gas analysis and are, like nitrogen, inert toward combustion, air may be regarded as 21 mole per cent oxygen and 79 mole per cent "atmospheric nitrogen." On a weight basis air is 23.2 per cent oxygen, and 4.31 lb of dry air are required to supply 1 lb of oxygen.

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[1] Noyes and Sherrill, "Chemical Principles," The Macmillan Company, New York, 1936.

The average molecular weight of air is 28.97. "Atmospheric nitrogen" has an average molecular weight of 28.17 or about 0.6 per cent greater than that of pure nitrogen. Other physical properties of "atmospheric nitrogen" differ only slightly from pure nitrogen; for example, the specific heats differ about 0.2 per cent.

2. Coal and Coke

a. Testing and Classification.—Because the properties of coal from different localities are extremely variable, various tests are necessary to specify the behavior of coal to be used for fuel or producing coke. These tests are largely empirical and their utility depends on a careful standardization of procedure. Below are listed publications of A.S.T.M. on standard methods:

D 17-16	Specifications for Foundry Coke
D 21-16	Method of Sampling Coal
D 121-30	Definitions of Terms Relating to Coal and Coke
D 141-23	Method of Shatter Test for Coke
D 166-24	Specifications for Gas and Coking Coals
D 167-24	Method of Test for Volume of Cell Space of Lump Coke
D 197-30	Method of Test for Fineness of Powdered Coal
D 271-37	Methods of Laboratory Sampling and Analysis of Coal and Coke
D 291-29	Method of Test for Cubic Foot Weight of Crushed Bituminous Coal
D 292-29	Method of Test for Cubic Foot Weight of Coke
D 293-29	Method of Test for Sieve Analysis of Coke
D 294-29	Method of Tumbler Test for Coke
D 310-34	Method of Test for Size of Anthracite
D 311-30	Method of Test for Sieve Analysis of Crushed Bituminous Coal
D 346-35	Method of Sampling Coke for Analysis
D 388-38	Specifications for Classification of Coals by Rank
D 389-37	Specifications for Classification of Coals by Grade
D 407-35T	Definition of the Terms Gross Calorific Value and Net Calorific Value of Fuels (Tentative)
D 408-37T	Method of Test for Grindability of Coal by the Ball-mill Method (Tentative)
D 409-37T	Method of Test for Grindability of Coal by the Hardgrove-machine Method (Tentative)
D 410-38	Method of Test for Screen Analysis of Coal
D 431-38	Method for Designating the Size of Coal from Its Screen Analysis
D 440-37T	Method of Drop Shatter Test for Coal (Tentative)
D 441-37T	Method of Tumbler Test for Coal (Tentative)
D 492-38T	Method of Sampling Coals Classed According to Ash Content (Tentative)
D 493-38T	Definitions for Varieties of Bituminous and Subbituminous Coals (Tentative)
E 11-38T	Specifications for Sieves for Testing Purposes (Wire-cloth Sieves, Round-hole and Square-hole Screens or Sieves) (Tentative)

TABLE H-1.—CLASSIFICATION OF COALS BY RANK[*]
(Prepared by the U.S. Bureau of Mines)

Class	Group	Limits of fixed carbon or Btu, mineral-matter-free basis	Requisite physical properties
I. Anthracite	1. Meta-anthracite	Dry F.C., 98 % or more (dry V.M., 2 % or less)	Nonagglomerating[†]
	2. Anthracite	Dry F.C., 92 % or more and less than 98 % (dry V.M. 8 % or less and more than 2 %)	
	3. Semianthracite	Dry F.C., 86 % or more and less than 92 % (dry V.M., 14 % or less and more than 8 %)	
II. Bituminous[‡]	1. Low-volatile bituminous coal	Dry F.C., 78 % or more and less than 86 % (dry V.M., 22 % or less and more than 14 %)	
	2. Medium-volatile bituminous coal	Dry F.C., 69 % or more and less than 78 % (dry V.N., 31 % or less and more than 22 %)	
	3. High-volatile A bituminous coal	Dry F.C., less than 69 % (dry V.M., more than 31 %); and moist[§] Btu 14,000[‖] or more	
	4. High-volatile B bituminous coal	Moist[§] Btu, 13,000 or more and less than 14,000[‖]	
	5. High-volatile C bituminous coal	Moist Btu, 11,000 or more and less than 13,000[‖]	Either agglomerating or nonweathering[¶]
III. Subbituminous	1. Subbituminous A coal	Moist Btu, 11,000 or more and less than 13,000[‖]	Both weathering and nonagglomerating
	2. Subbituminous B coal	Moist Btu, 9500 or more and less than 11,000[‖]	
	3. Subbituminous C coal	Moist Btu, 8300 or more and less than 9500[‖]	
IV. Lignitic	1. Lignite	Moist Btu, less than 8300	Consolidated
	2. Brown coal	Moist Btu, less than 8300	Unconsolidated

F.C. = fixed carbon.

V.M. = volatile matter.

[*] This classification does not include a few coals which have unusual physical and chemical properties and which come within the limits of fixed carbon or Btu of the high-volatile bituminous and subbituminous ranks. All these coals either contain less than 48 per cent dry, mineral-matter-free fixed carbon or have more than 15,500 moist, mineral-matter-free Btu.

[†] If agglomerating, classify in low-volatile group of the bituminous class.

[‡] It is recognized that there may be noncaking varieties in each group of the bituminous class.

[§] Moist Btu refers to coal containing its natural bed moisture but not including visible water on the surface of the coal.

[‖] Coals having 69 per cent or more fixed carbon on the dry, mineral-matter-free basis shall be classified according to fixed carbon, regardless of Btu. Heating values are gross.

[¶] There are three varieties of coal in the high-volatile C bituminous coal group; variety 1, agglomerating and nonweathering; variety 2, agglomerating and weathering; variety 3, nonagglomerating and nonweathering.

The properties most important for use as fuel are as listed below:

1. Heating value.
2. Proximate analysis:
   Moisture (loss at 105°C for 1 hr)
   Volatile matter (additional loss on ignition at 950°C)
   Ash (residue after burning)
   Fixed carbon (remainder)
3. Fusing point of ash.
4. Ultimate analysis, % C, H, N, O, and S.

There are numerous systems of classifying coal all of which have advantages and defects. The most widely used is the U.S. Bureau of Mines classification which has been adopted by the A.S.T.M. and the A.S.A. This classification, which is based on the proximate analysis, is presented in Table H-1 (page 275).

b. Typical Analyses of Coals.—Coal analyses of the United States are presented in Table H-2. These data are only illustrative unless the reader is interested in one of these few coals. Fortunately thousands of coal analyses are published by the U.S. Bureau of Mines and similar organizations, so that specific data may usually be obtained on any particular coal. The analyses of some typical cokes are given in Table H-3. The ultimate analysis is given on the ash- and moisture-free basis in accordance with custom. The advantage of this is to exclude the hydrogen and oxygen present in the ash and water from combustion calculations. This distinction, though not precise, affords a sound workable method.

c. Heating Value of Coal.—The heating value of coal determines the amount required to supply a given quantity of heat. Though best determined directly, gross heating values may be predicted with reasonable accuracy from the ultimate analysis by the modified Dulong formula (or by the equivalent factors from Table H-4).

$$\text{Btu/lb} = 155.44C + 621\,(H - \tfrac{1}{8}O) + 40.5S$$

where C = carbon %
H = hydrogen %
O = oxygen %
S = sulphur %

If the ultimate analysis is expressed in the ash- and moisture-free basis, the calculated heating value will be on the same basis and the heating value based on the coal as received may be obtained by multiplying by the following factor:

$$\frac{100}{100 - \%\ \text{ash} - \%\ \text{moisture}}$$

TABLE H-2.—ANALYSES OF TYPICAL UNITED STATES COALS

Coal		As-received basis							Ash- and moisture-free basis				
		Moisture											
No.	Source: bed or mine	Loss by air drying, %	Total %	Volatile matter, %	Fixed carbon, %	Ash, %	Gross heating value, Btu/lb	Softening point of ash, °F	% C	% H	% O	% N	% S
1	Buck Mountain..	2.4	5.2	2.8	85.3	6.7	13,090	....	95.0	1.9	2.0	0.7	0.4
2	Pocahontas......	1.0	1.6	17.4	74.5	6.5	14,400	2780	91.1	4.5	2.4	1.3	0.7
3	Lower Freeport..	1.1	2.0	24.9	66.7	6.4	14,310	2840	88.6	5.3	3.8	1.5	0.8
4	Black Creek.....	1.2	3.1	36.0	58.3	2.6	14,190	2390	84.0	5.7	7.2	1.9	1.2
5	Pittsburgh.......	0.5	2.0	41.3	48.7	8.0	13,320	2090	80.6	5.7	7.5	1.3	4.9
6	No. 6 Illinois....	....	7.9	32.1	47.7	12.3	11,540	2360	82.2	5.3	9.8	1.7	1.0
7	Eureka Navy....	2.4	4.4	35.5	47.9	12.2	12,310	....	81.9	6.3	8.9	2.1	0.8
8	No. 1 Wyoming..	4.3	10.8	37.7	47.8	3.7	11,750	....	78.0	5.5	13.8	1.5	1.2
9	Newcastle.......	4.4	10.9	36.1	37.0	16.0	9,910	....	75.9	6.5	15.3	1.8	0.5
10	Black Diamond..	5.8	11.1	37.3	44.8	6.8	11,600	(2470)	79.5	5.8	12.5	1.4	0.8
11	Colstrip.........	....	25.1	28.5	38.8	7.6	......	....	76.7	5.2	16.2	1.1	0.8
12	Knife River.....	26.5	35.6	26.2	32.6	5.6	7,130	....	72.0	4.7	21.1	1.0	1.2

DETAILED DESCRIPTION OF COALS AND REFERENCES

1. Buck Mountain bed, bottom bench, coal from Highland No. 5 Mine, Luzern County, Pa., *U.S. Bur. Mines Tech. Paper* 512.

2. Pocahontas No. 3 bed coal from Buckeye No. 3 Mine, Stephanson, Wyoming County, W. Va. *U.S. Bur. Mines Tech. Paper* 604.

3. Lower Freeport bed coal from Indiana County, Pa. *U.S. Bur. Mines Tech. Paper* 621.

4. Black Creek bed coal from Empire Mine, Walker County, Ala. *U.S. Bur. Mines Tech. Paper* 531.

5. Pittsburgh bed coal from Pittsburgh Terminal No. 9 Mine, Washington County, Pa. *U.S. Bur. Mines Tech. Paper* 571.

6. No. 6 bed coal from Orient No. 2 Mine, West Frankport, Franklin County, Ill. *U.S. Bur. Mines Tech. Paper* 524.

7. Navy No. 6 Lower Bench coal from Eureka Navy Mine, Cumberland, King County, Wash. *U.S. Bur. Mines Tech. Paper* 512.

8. No. 1 bed coal from Rock Springs Mine No. 4, Rock Springs, Sweetwater County, Wyo. *U.S. Bur. Mines Tech. Paper* 512.

9. Upper Bagley bed coal from Newcastle Mine, King County, Wash. *U.S. Bur. Mines Tech. Paper* 512.

10. Black Diamond bed coal from Gallup Southwestern Mine, Gallup, McKinley, County, N.M. *U.S. Bur. Mines Tech. Paper* 569.

11. Rosebud bed coal from Colstrip Mine, Rosebud County, Mont. *U.S. Bur. Mines Tech. Paper* 622.

12. Lignite from Knife River Mine, Beulah, Mercer County, N.D. *U.S. Bur. Mines Tech. Paper* 512.

TABLE H-3.—ANALYSES OF COKES
(Marks, "Mechanical Engineers' Handbook," 4th ed., McGraw-Hill Book Company, Inc., New York, 1941)

Kind of process	As-received basis									
	Proximate, %				Ultimate, %					High heat value, Btu/lb
	Moisture	Volatile matter	Fixed carbon	Ash	Hydrogen	Carbon	Nitrogen	Oxygen	Sulphur	
Gas-works coke:*										
Horizontal retorts	0.8	1.4	88.0	9.8	0.7	86.8	1.1	0.9	0.7	12,820
Vertical retorts	1.3	2.5	86.3	9.9	1.1	85.4	1.4	1.5	0.7	12,770
Narrow coke ovens	0.7	2.0	85.3	12.0	0.6	84.6	1.2	0.9	0.7	12,550
By-product coke†	0.8	1.4	87.1	10.7	0.8	85.0	1.3	1.2	1.0	12,690
Beehive coke†	0.5	1.8	86.0	11.7	0.8	84.4	1.2	0.9	1.0	12,527
Low-temperature coke‡	0.0	9.8	83.5	6.7	3.2	84.2	1.9	3.2	0.8	14,030
Low-temperature coke	2.8	15.1	72.1	10.0	3.5	74.5	1.6	8.6	1.8	12,600
Pitch coke†	0.3	1.1	97.6	1.0	0.6	96.6	0.7	0.6	0.5	14,097
Petroleum coke	1.1	7.0	90.7	1.2	3.3	90.8	0.8	3.1	0.8	15,060

* Davis and Greene, Reactivity of Pulverized Cokes in Air, Carbon Dioxide, and Water Vapor, *Am. Gas Assoc. Proc.*, 1926, pp. 1160–1164.

† Kinney and Perrott, The Shatter and Tumbler Tests for Metallurgical Coke, *Ind. Eng. Chem.*, **14**, 1922, pp. 926–931.

‡ Fieldner and Davis, Gas-, Coke-, and Byproduct-making Properties of American Coals and Their Determination, *U.S. Bur. Mines Monograph* 5, 1934.

The heating value of coal may also be predicted from the proximate analysis alone, by using Fig. H-1.

d. Combustion Properties of Coal Constituents.—Table H-4 gives the combustion properties of the elements commonly found in coal. This table is intended to facilitate calculations based on the ultimate analysis of coal. Use of this table is illustrated in Examples H-1, H-3, and H-4 given later in this chapter. The calculation of these factors is illustrated by Example H-5.

e. Types of Coal Stokers.—Except for small units, coal is seldom hand-fired. Table H-5 summarizes information on stokers. The coking properties, the quantity and fusing points of ash, and the amount of volatile matter determine the relative advantages of the different types of stoking equipment.

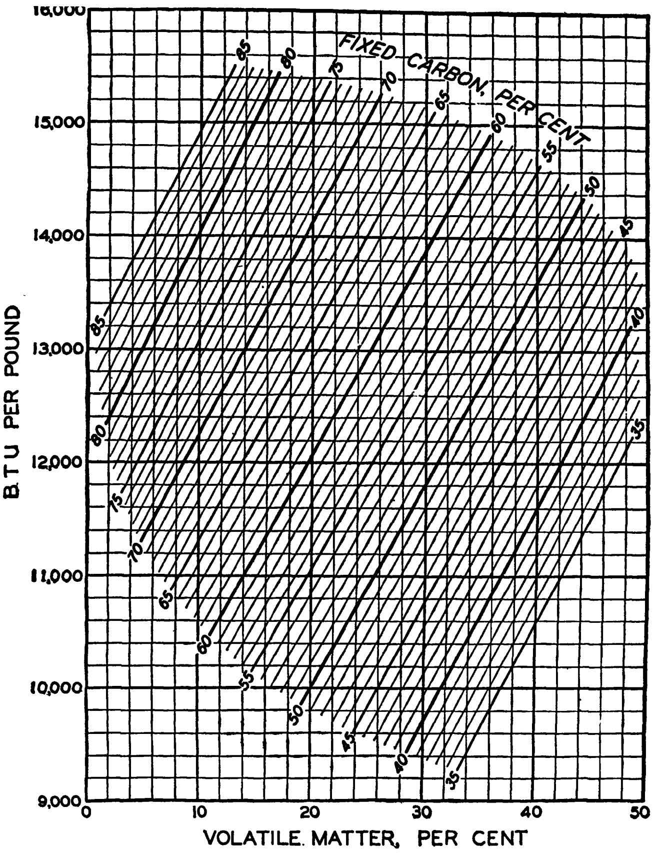

FIG. H-1.—Heating value of coals from proximate analysis. This chart will give approximate results (±300 Btu per lb) for eastern coals containing less than 10 per cent moisture and normal amounts of ash. (*Based on results published in Analyses of Coals, U. S. Bur. Mines Bull. 22, reprinted from Graf, "Gas Engineers' Handbook," McGraw-Hill Book Company, Inc., New York,* 1934.)

High ash content is obviously undesirable because of the cost of disposal and because some of the heating value is inevitably lost as unburned coke carried by the ash. Ash content of fines is usually higher than that of the larger sizes from the same mine. Frequently the ash content may be reduced by washing. Clinker formation is favored by high ash content and by low fusing point. Ashes fusing in the range of 1900 to 2200°F are considered low fusing; those above 2600°F are considered high fusing. The fusing point alone is not a clear-cut criterion of tendency to clinker. In some of the larger furnaces the fuel bed is kept at a high temperature and the ash is tapped off as molten slag. This type of operation is very advantageous for handling coals with low-fusing ash.

The burning of coal takes place in two zones: on the fire bed itself (primary combustion) and in the flame above (secondary combustion). This arises for two reasons: (1) a large portion of the coal is volatilized on heating to the temperature of the fire bed; (2) the primary combustion is seldom complete. In practice, therefore, considerable space is provided above the fire bed for secondary combustion and some of the air is admitted directly to the firebox. The combustion volume required obviously depends on the amount of the coal volatilized. The volatile matter determination of the proximate analysis is a semiquantitative measure of the fraction of coal volatilized and is, therefore, a rough measure of the secondary combustion requirements for volume and air.

TABLE H-4.—COMBUSTION PROPERTIES OF COAL AND COKE CONSTITUENTS

Element	Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur
Formula	C	H	O	N	S
Atomic weight	12.010	1.008	16.000	14.008	32.06
Free element at 60°F, 30 in. Hg	Solid, graphite	Gas, H_2	Gas, O_2	Gas, N_2	Solid, rhombic
Gross heating value, Btu/lb:					
1. As free element	14,100	61,042	0	0	3,983
2. Apparent in coal (Dulong)	15,544	62,100	−7,762	0	4,050
Theoretical air required:					
1. Weight, lb/lb combustible	11.48	34.26	−4.31	0	4.30
2. Volume, SCF/lb combustible	150.0	447.8	−56.3	0	56.2
Primary products of combustion with oxygen:					
1. Formula	CO_2	H_2O	[*]	N_2	SO_2
2. Weight, lb/lb combustible	3.668	8.936	....	1.000	1.998
3. Volume, SCF/lb combustible	31.38	188.7	....	13.52	11.69
Nitrogen[†] in products of combustion with theoretical air:					
1. Weight, lb/lb combustible	8.82	26.31	−3.31	1.00	3.30
2. Volume, SCF/lb combustible	118.5	353.6	−44.5	13.5	44.4

[*] Oxygen included in products of combustion of the other elements.

[†] Includes argon and other inert gases reported as nitrogen in standard gas analyses.

f. Powdered Coal.—The use of coal in powdered form is very advantageous for securing efficient combustion with low-cost operation and maintenance. Further, a furnace may readily be designed for alternate use of powdered coal, fuel oil, or gas. Since the ash is partly blown out of the stack, provision for ash removal may be required, particularly in urban communities. Fineness of grinding is important and is conveniently determined by a screen analysis using, say, 50-, 100-, and 200-mesh screens. Blake and Purdy[1] give typical screen analyses, as shown in the accompanying table.

TABLE H-5.—SUMMARY OF INFORMATION ON STOKERS
(Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York, 1941)

	Chain grates	Overfeed stokers	Underfeed stokers
Description	Fuel from hopper is carried horizontally into furnace on a continuous web. The web is cooled coming out through the ashpit and returns to coal hopper	Grate extends from hopper into furnace at a rather steep incline, although coal flows down only if a rocking or plunger movement is imparted to grate bars	Raw coal is pushed up through the fuel bed and cinder falls off onto cinder plate. Gases are distilled in an oxidizing atmosphere. Capable of high overloads
Fuel used	1. Coke breeze, steam sizes of anthracite, or 2. High-volatile midwestern coals. In general, any noncoking, clinkering coal may be used, but preferably no mixtures	All coals can be used. Good all-round stoker Is mainly used on midwest fuels. Coking coals can be used. Will burn refuse fuels	High-volatile coals, coking coals, and slack or fines may be burned. Ash must not be easily fusible
Draft	Natural: 0.25 to 0.60 in. water Forced: 1- to 2-in. water pressure with coke 1- to 4-in. water pressure with Illinois and similar coals	Natural: 0.25 to 0.60 in. water Forced: 1- to 3-in. water pressure	All forced draft Normal: 2- to 4-in. water pressure in wind box Maximum: 5 to 7-in. water pressure in wind box
Rate of combustion, lb per sq ft per hr	Average: 30–35 Maximum: 45–60 10 lb per 0.1 in. water, for natural drafts	Average: 25–35 Maximum: 40–50	Average: 30–40 Maximum: 60–80 10 lb per 1-in. water pressure
Means of regulation	1. Height of coal grate 2. Speed of grate 3. Amount and distribution of air	1. Rate of plunger feeder 2. Rate of ash removal 3. Amount and distribution of air	1. Rate of feed 2. Amount and distribution of blast
Miscellaneous	Watch for live coals going over end of grate	Fireman needed for ash removal at times and fire must be cleaned	Air is admitted over clinker plate to burn out cinder. Fuel bed from 12 to 24 in. deep

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[1] Perry, "Chemical Engineers' Handbook," McGraw-Hill Book Company, Inc., New York, 1941.

	Low-volatile coal, %	High-volatile coal, %
Through:		
50-mesh	99.5	99
100-mesh	95	90
200-mesh	80	65

The power required for pulverizing coal depends on the dryness and the properties of the particular coal. This may be estimated by one of the A.S.T.M. methods listed earlier. Dry coal requires considerably less power but is considerably dustier. Figure H-2 gives the power required for pulverizing a Pennsylvania bituminous coal.

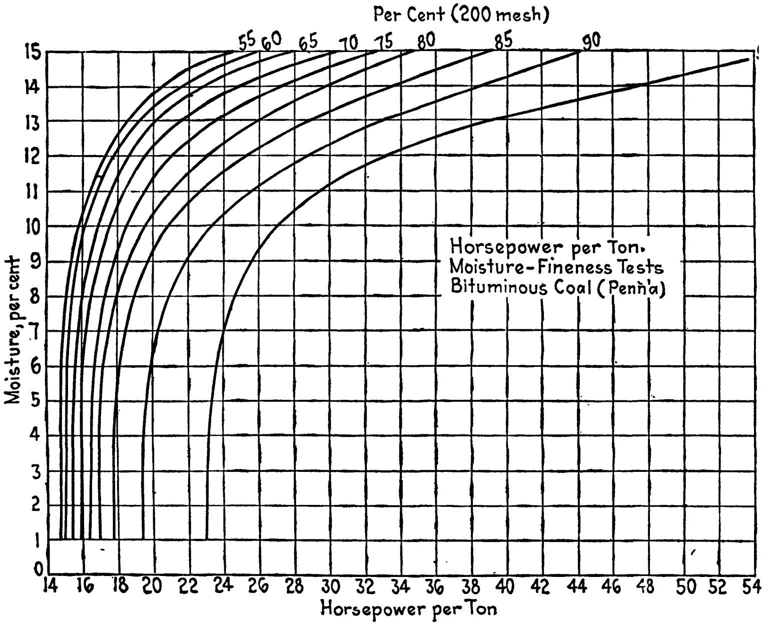

FIG. H-2.—Relation between power consumption, fineness, and moisture content in pulverizing Pennsylvania bituminous coal. (*Haslam and Russell, "Fuels and Their Combustion," McGraw-Hill Book Company, Inc., New York,* 1926.)

g. Storage of Coal.—Four things may occur to stored coal: (1) spalling from alternate wetting and drying, (2) loss of heating value owing to oxidation, (3) impairment of coking properties and, (4) spontaneous combustion.

Spalling may be serious in the case of low-rank coals but is less important in the case of bituminous or anthracite coals. The loss of heating value is generally small, in the order of 1 per cent per year.

Since some gain in weight accompanies the oxidation, the pile loss is somewhat less than indicated by the heating value per pound. Loss in coking properties is not usually serious and is no disadvantage for coal to be used as fuel.

Spontaneous combustion deserves careful consideration.[1] Coal temperature should be watched and the coal moved if the temperature goes over 120°F. Avoiding the segregation of sizes and the storing of larger sizes is helpful. Avoiding too high piles is also a good precaution. Wetting the coal does *not* retard oxidation.

Storage of coal above ground is limited in some localities by law.

3. Fuel Oil

a. Fuel-oil Specification.—Table H-6 gives specifications of five grades of oil. It will be noted that the former Grade 4 has now been omitted from the list. Grades 5 and 6 are frequently referred to as Bunker B and Bunker C. The heavier oils are cheaper and more popular for large units, whereas the lighter grades are usually employed

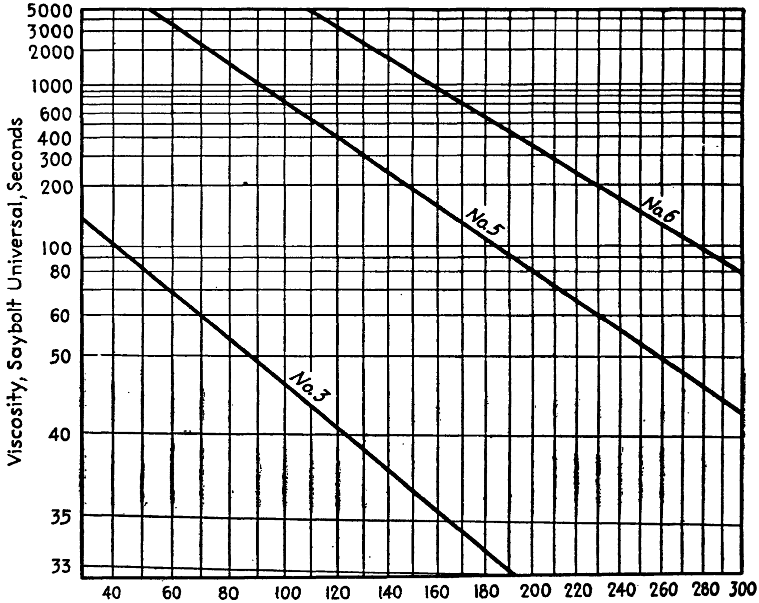

FIG. H-3.—Approximate maximum viscosity of three grades of fuel oils.

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[1] For a brief discussion see comments by Fieldner; Marks, "Mechanical Engineers' Handbook," 4th ed., McGraw-Hill Book Company, Inc., New York, 1941.

TABLE H-6.—DETAILED REQUIREMENTS FOR FUEL OILS*
[*Nat. Bur. Standards Com. Standard* CS12-40 (1940)]

Grade†		Flash point, °F		Pour point, °F	Water and sediment, %	Carbon residue, %	Ash, %	Distillation temperatures, °F				Viscosity sec			
								10% point	90% point		End point	Saybolt Universal at 100°F		Saybolt Furol at 122°F	
No.	Description of fuel oil	Min	Max	Max	Max	Max	Max	Max	Max	Min	Max	Max	Min	Max	Min
1	Distillate oil for use in burners requiring a volatile fuel	100 or legal	165	0	Trace	0.05 on 10% residuum§	....	410	...	.....	560‖				
2	Distillate oil for use in burners requiring a moderately volatile fuel	110 or legal	190	10‡	0.05	0.25 on 10% residuum¶	....	440	600						
3	Distillate oil for use in burners requiring a low-viscosity fuel	110 or legal	230	20‡	0.10	0 15 straight	....	...	675	600**	....	45			
5	Oil for use in burners requiring a medium-viscosity fuel	130 or legal	...	...	1.00	....	0.10	...	...	.....	....	..	50	40	
6	Oil for use in burners equipped with preheaters, permitting a high-viscosity fuel	150	...	...	2.00††	....	....	...	...	.....	....	..	..	300	45

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* Recognizing the necessity for low-sulphur fuel oils used in connection with heat-treatment, nonferrous metal, glass, and ceramic furnaces, and other special uses, a sulphur requirement may be specified in accordance with the following table:

Grade of Fuel Oil, No.	Sulphur (max.), %
1	0.5
2	0.5
3	0.75
5	No limit
6	No limit

Other sulphur limits may be specified only by mutual agreement between the buyer and seller.

† It is the intent of these classifications that failure to meet any requirement of a given grade does not automatically place an oil in the next lower grade unless in fact it meets all requirements of the lower grade.

‡ Lower or higher pour points may be specified whenever required by conditions of storage or use. However, these specifications shall not require a pour point lower than 0°F under any conditions.

§ For use in other than sleeve-type blue-flame burners, carbon residue on 10 per cent residuum may be increased to a maximum of 0.12 per cent. This limit may be specified by mutual agreement between the buyer and seller.

‖ The maximum end point may be increased to 590°F when used in burners other than sleeve-type blue-flame burners.

¶ To meet certain burner requirements, the carbon-residue limit may be reduced to 0.15 per cent on 10 per cent residuum.

** The minimum distillation temperature of 600°F for 90 per cent may be waived if A.P.I. gravity is 26 or lower.

†† Water by distillation, plus sediment by extraction. Sum, maximum 2.0 per cent. The maximum sediment by extraction shall not exceed 0.50 per cent. A deduction in quantity shall be made for all water and sediment in excess of 1.0 per cent.

TABLE H-7.—COMPOSITION AND PROPERTIES OF VARIOUS OILS
("Combustion," 3d ed., American Gas Association, New York, 1932)

	A.P.I gravity, °Bé	Specific gravity at 60°F	Lb/gal	Per cent bottom sediment (centrifuge method)	Pour point, °F	Viscosity		Analysis, weight basis, %					Heating value (bomb calorimeter)		
						furol sec	At °F	Water	Sulphur	Carbon	Hydrogen	Undetermined	Gross Btu/lb	Net* Btu/lb	Gross Btu/gal
Domestic fuel oils															
Commercial gasoline	55.5	0.7567	6.304	....	..	...	...	....	....	84.3	15.7	....	21,000	19,506	132,384
Commercial kerosene	41.8	0.8165	6.802	....	..	...	...	....	0.02	84.7	15.3	....	20,000	18,545	136,040
Gas oil—Kansas	35.0	0.8498	7.080	....	..	...	...	....	0.18	....	.....	....	19,748	......	139,816
Gas oil—Oklahoma	32.0	0.8654	7.210	....	..	...	...	....	0.21	....	.....	....	19,474	......	140,407
Straight-run fuel oils															
California	26.2	0.8973	7.475	0.10	42	14	77	0.89	1.19	85.8	12.09	0.04	19,053	18,001	142,421
Oklahoma Mid-Continent	25.3	0.9024	7.518	0.05	32	60	77	....	0.46	86.4	12.38	0.76	19,353	18,173	145,496
Mixed Kansas Mid-Continent	25.5	0.9013	7.509	0.10	38	23	77	....	0.46	86.5	12.38	0.76	19,182	18,002	144,031
Mixed Kansas Mid-Continent	25.1	0.9036	7.528	0.10	38	16	122	0.33	0.39	86.2	12.39	0.69	19,256	18,076	144,956
Archer & Wichita Cos., Texas	25.5	0.9013	7.509	0.05	32	42	77	0.11	0.60	....	.....	....	19,277	18,093	144,758
Low-level cracked residuums															
California	16.5	0.9561	7.965	0.10	Below 0	13	77	0.05	1.14	87.5	10.17	1.14	18,319	17,551	145,911
Oklahoma Mid-Continent	14.3	0.9705	8.085	0.00	Below 0	57	77	0.05	0.70	87.6	10.27	1.38	18,454	17,479	149,200
Mixed Kansas Mid-Continent	22.0	0.9218	7.680	0.20	Below 0	14	77	0.05	0.42	87.4	11.10	1.03	18,778	17,723	144,215
Mixed Kansas Mid-Continent	8.1	1.0140	8.448	0.80	Below 0	24	122	0.25	0.67	88.5	9.07	1.51	18,077	17,212	152,714
Archer & Wichita Cos., Texas	18.6	0.9427	7.854	0.80	Below 0	20	77	....	0.79	....	.....	....	18,732	17,781	147,121
Flashed cracked residuums															
California	8.9	1.0070	8.389	0.30	21	174	77	0.05	1.20	88.3	9.50	0.95	18,084	17,179	151,707
Oklahoma Mid-Continent	10.7	0.9951	8.290	0.20	43	124	122	....	0.77	88.5	9.92	0.81	18,293	17,349	151,649
Mixed Kansas Mid-Continent	8.6	1.0110	8.423	1.00	2[illegible]	52	122	....	0.56	88.9	9.80	0.74	18,277	17,345	153,947
Mixed Kansas Mid-Continent	9.2	1.0030	8.356	2.60	42	159	122	0.40	0.68	88.4	9.95	0.81	18,274	17,324	152,697

* Gross Btu/lb observed −[(lb H × 9) + lb H_2O present] 1057 = net Btu/lb

for small units because of their greater convenience. Table H-7 gives data on the composition and properties of several oils.

The flash and fire points are of importance in determining conditions for safe handling. An oil below the flash point is safe since insufficient vapors are produced for possible ignition. The carbon residue and distillation data are of importance if the burner is designed to vaporize a considerable portion of the oil.

The viscosity of the oil is important to the process engineer for sizing pipe lines and determining the temperature to which the oil must be heated for burner use. The most favorable viscosity is, of course, determined by the particular burner; however, Trinks[1] recommends 300 Saybolt Universal as a general working figure. The effect of temperature on viscosity differs considerably for different oils; nevertheless, the relation is qualitatively the same so that the temperature required for a given viscosity may be estimated to within 10 or 20°F by use of Fig. H-3, page 283.

As in the case of coal, an ultimate analysis may be made, but this usually serves no useful purpose because fuel oils differ only slightly in composition. Table H-7 gives the analyses of several oils.

b. Heating Values of Fuel Oils.—These range between 130,000 and 153,000 Btu/gal (gross). The light oils generally have the lower heating values per gallon but higher per pound; conversely, the heavier oils have larger heating values per gallon though less per pound. The heating value of a fuel oil should be directly determined. However, in the absence of specific data approximate values may be obtained by use of Fig. H-4.

c. Types of Oil Burners.—Efficient performance of a burner depends on its ability to atomize the oil and mix thoroughly with the air stream before the ignition zone. This atomization may be effected by high- or low-pressure air, by steam, or by mechanical means. Table H-8 gives data on air atomization. Haslam and Russell[2] state that between $\frac{1}{16}$ and 1 lb of steam is required to atomize 1 lb of fuel. Oil may also be atomized by pressuring through liquid spray nozzles. In general 75 to 150 psi head pressure is required. Rotary burners atomize oil by a combination of air flow and centrifugal force of a rotating cylinder. These burners are very flexible. Although they may be made very efficient, usually their efficiency is low and large excesses of air (100 to 200 per cent) may be required.

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[1] Trinks, "Industrial Furnaces," 2 vols., John Wiley & Sons, Inc., New York, 1942.

[2] "Fuels and Their Combustion," McGraw-Hill Book Company, Inc., New York, 1926.

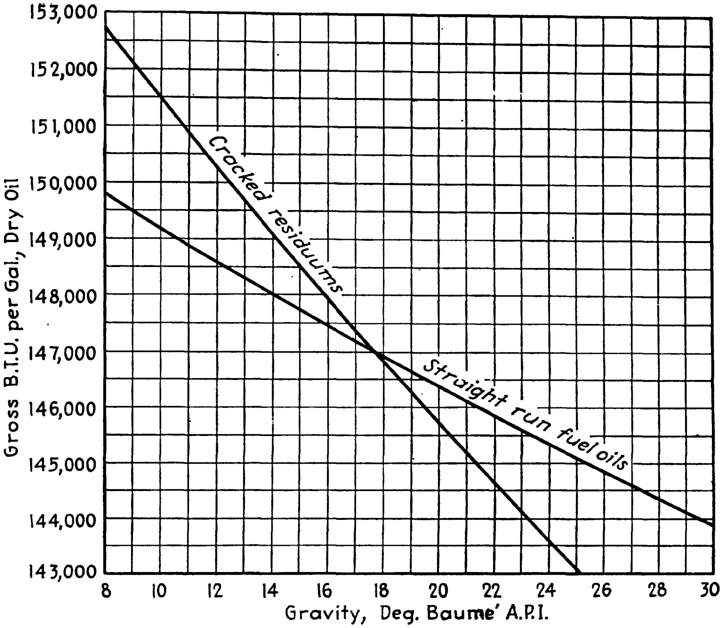

FIG. H-4.—Relation between heating value of dry fuel oil and A.P.I. gravity. (*"Combustion,"* 3*d ed., American Gas Association, New York,* 1932.)

TABLE H-8.—BURNER PERFORMANCE WITH DIFFERENT TYPES OF AIR ATOMIZATION (Haslam and Russell, "Fuels and Their Combustion," McGraw-Hill Book Company, Inc., New York, 1926)

Type	Velocity of atomizing air, fps	Per cent of air for combustion used for atomization
Low-pressure (turboblower) air atomization, 10 oz per sq in............	300	60
Low-pressure (positive-pressure pump) air atomization, 2 psi.............	500	50
High-pressure air atomization, 50 psi..	2,500	12

d. Combustion Properties of Constituents of Fuel Oil.—The data given in Table H-4 for coal and coke may be used. As the heating value of oils computed by this method will, however, generally be about 600 Btu/lb below the actual value, this particular use of the table is not recommended. For other purposes the table is reliable.

4. Gaseous Fuels

a. Analyses.—Gaseous fuels are usually analyzed by either the traditional absorption and combustion analyses or by low-temperature distillations.

Carbon dioxide, oxygen, illuminants, hydrogen, carbon monoxide, methane, ethane, and nitrogen are the quantities usually determined by absorption and combustion analyses. These analyses are reasonably specific except for the hydrocarbons. The illuminants include acetylene, aromatics, higher olefins, and isobutane in addition to ethylene, the principal constituent. Some of these components may be determined separately. The methane and ethane reported will be fictitious if other saturated hydrocarbons are present, that is, 15 per cent CH_4, 5 per cent C_2H_6, and 1.0 per cent C_3H_8 would be reported as 14 per cent CH_4 and 7 per cent C_2H_6. For combustion purposes this is not at all serious as the calculated heating values and products of combustion will be correct. Any sulphur dioxide or hydrogen sulphide present will be reported as carbon dioxide, unless separately determined.

If considerably higher hydrocarbons are present, analysis by low-temperature distillation is advisable. This low-temperature analysis, however, does not distinguish among H_2, CH_4, CO, N_2, and O_2. Further, carbon dioxide and acetylene are usually removed before analysis. Consequently such constituents must be determined separately.

b. Units of Measurement.—Fuel gases are customarily measured as cubic feet. Because the amount of gas contained in a cubic foot varies with temperature and pressure, it is necessary to define the conditions of measurement. The most widely used standard is that of the American Gas Association which defines a standard cubic foot (SCF) as the quantity of gas contained in a cubic foot of space at 60°F and 30 in. of mercury (14.73 psi) absolute pressure. The gas volumes are usually based on actual physical measurements, though frequently perfect gas volumes are used for simplicity, as this avoids any difficulty in choice of values for components that are liquid at the standard conditions.

Gas sales are generally contracted on the basis of one of three tables as adopted by the American Gas Association,[1] the Natural Gasoline Association of America,[2] or the California Natural Gasoline

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[1] "Fuel—Flue Gases," American Gas Association, New York, 1940; cf. Perry, *op. cit.*

[2] "Technical Manual," 4th ed., Natural Gasoline Supply Men's Association, Tulsa, 1942.

Association.[1] Unfortunately these tables are not in agreement. The American Gas Association values are based on actual gas volumes for true gases, and perfect gas volumes for vapors of liquids. The California Natural Gasoline Association values are based on the perfect gas law (using a different value of the gas constant than is employed in this book). They give factors for gas-law deviation correction and recommend procedures for applying these to metering[2] and correction of gas analyses.[3] The values in the Natural Gasoline Association of America table are not self-consistent.

These differences, though the cause of considerable irritation, are in reality no great cause for concern, since the differences involved are less than the usual accuracies of gas analysis and measurement. The values given in this chapter are taken largely from these three tables or references quoted by them. No claim is made that the values chosen are the best available; however, an effort has been made to make the given data self-consistent. Values are given on both the perfect gas and the actual volume basis so that the reader may choose whichever standard appears more suitable.

Though this book uses only the American Gas Association standard conditions to define the cubic foot, it should be stated that many other standards of gas measurement are employed. The compressed gas industry uses 70°F and standard atmospheric pressure (14.70 psi) as the basis of gas measurement. Other standards are occasionally encountered: 60°F and 14.70 psi; 60°F and 14.40 psi; and 32°F and 14.70 psi.

c. **Typical Fuel Gases.**—Table H-9 gives analyses, properties, and combustion products of some commercial fuels.

d. **Properties of Constituents of Gaseous Fuels.**—Very fortunately nearly all properties of fuel gases are additive, and the properties of any fuel gas (at low pressure at least) may be readily computed from those of its constituents. As already mentioned under Units of Gas Measurement, there are two methods of doing this: by perfect gas volumes or by actual gas volumes. This choice is largely arbitrary and is left to the reader's judgment.

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[1] Matteson and Hanna, *Proceedings* of the April, May, June, 1942, meetings, California Natural Gasoline Association; cf. *Oil Gas J.*

[2] Tentative Standards for the Determination of Superexpansibility Factors in High Pressure Gas Measurement, *California Natural Gasoline Association*, Bull. TS-354 (1936).

[3] Tentative Standard Method for Analysis of Natural Gas and Gasoline by Fractional Distillation, *California Natural Gasoline Association*, Bull. TS-411 (1941).

TABLE H-9.—PROPERTIES OF TYPICAL COMMERCIAL GASES
("Combustion," 3d ed., American Gas Association, New York, 1932)

No.	Gas	Constituents of gas—% by volume									Sp gr	Cu ft air req. for comb. of cu ft of gas	Btu/ cu ft gross	Btu/ cu ft net	Products of combustion per cu ft of gas				Ultimate % CO_2	Btu net/ cu ft of prod. of comb.	Flame temp., no excess air
		CO_2	O_2	N_2	CO	H_2	CH_4	C_2H_6	Illuminants						H_2O	CO_2	N_2	Total			
									C_2H_4	C_6H_6											
1	Natural gas (Birmingham)	....	....	5.0	....	....	90.0	5.0	....	....	0 60	9.41	1002	904	2.02	1.00	7.48	10.50	11.8	86.0	3565
2	Natural gas (Pittsburgh)	....	....	0.8	....	....	83.4	15.8	....	....	0.61	10.58	1129	1021	2.22	1.15	8.37	11.73	12.1	87.0	3562
3	Natural gas (So. California)	0.7	....	0 5	....	....	84.0	14.8	....	....	0.64	10.47	1116	1009	2.20	1.14	8.28	11.62	12.1	87.0	3550
4	Natural gas (Los Angeles)	6.5	....	....	....	....	77.5	16.0	....	....	0.70	10.05	1073	971	2 10	1.16	7.94	11.20	12.7	86.7	3550
5	Natural gas (Kansas City)	0.8	....	8.4	....	....	84.1	6.7	....	....	0 63	9.13	974	879	1.95	0.98	7.30	10.23	11.9	86.0	3535
6	Reformed natural gas	1.4	0.2	2.9	9.7	46.6	37.1	....	1.3	(C_3H_6 0.8)	0.41	5.22	599	536	1.30	0.53	4.16	5.99	11.3	89.6	3615
7	Mixed, natural, and water gas	4.4	2.1	4.7	25.5	35.1	23.1	4.7	0.2	0.2	0.61	4 43	525	477	1.01	0.64	3 55	5.20	15.3	91.7	3630
8	Coke-oven gas	2.2	0.8	8.1	6.3	46.5	32.1	....	3.5	0.5	0.44	4.99	574	514	1.25	0.51	4.02	5.78	11.2	87.0	3610
9	Coal gas (continuous verticals)	3.0	0.2	4.4	10.9	54.5	24.2	....	1.5	1.3	0.42	4.53	532	477	1.15	0 49	3.62	5.26	11.9	90.7	3645
10	Coal gas (inclined retorts)	1.7	0.8	8.1	7.3	49.5	29.2	....	0.4	3.0	0.47	5.23	599	540	1.23	0.57	4.21	6.01	11.9	89.9	3660
11	Coal gas (intermittent verticals)	1.7	0.5	8.2	6.9	49.7	29.9	....	3.0	0.1	0.41	4.64	540	482	1.21	0.45	3.75	5.41	10.7	89.0	3610
12	Coal gas (horizontal retorts)	2.4	0.75	11.35	7.35	47.95	27.15	....	1.32	1.73	0.47	4.68	542	486	1.15	0.50	3.81	5.46	11.6	89.0	3600
13	Mixed coke-oven and carbureted water gas	3.4	0.3	12.0	17.4	36.8	24.9	....	3.7	1.5	0.58	4.71	545	495	1.04	0.62	3.85	5.51	13.9	90.0	3630
14	Mixed coal, coke-oven, and carbureted water gas	1.8	1.6	13.6	9.0	42.6	28.0	....	2.4	1 0	0.50	4.52	528	475	1.11	0.50	3.71	5.32	11.8	89.3	3640
15	Carbureted water gas	3.0	0 5	2.9	34.0	40.5	10.2	....	6.1	2.8	0.63	4.60	550	508	0.87	0.76	3.66	5 29	17.2	96.2	3725
16	Carbureted water gas	4.3	0.7	6.5	32.0	34.0	15.5	....	4.7	2.3	0.67	4.51	534	493	0.75	0 86	3.63	5.24	17.1	94.2	3700
17	Carbureted water gas (low gravity)	2.8	1.0	5.1	21.0	47.5	15.0	....	5.2	2.4	0.54	4.61	549	501	0.98	0.64	3.70	5 31	14.7	94.3	3690
18	Water gas (coke)	5.4	0 7	8.3	37.0	47.3	1.3	....	....	....	0.57	2.10	287	262	0.53	0.44	1.74	2.71	20 1	96.6	3670
19	Water gas (bituminous)	5.5	0 9	27.6	28.2	32.5	4.6	....	0.4	0.3	0.70	2.01	261	239	0.47	0.41	1.86	2.74	18 0	87.2	3510
20	Oil gas (Pacific coast)	4.7	0.3	3.6	12.7	48.6	26.3	....	2.7	1.1	0.47	4.73	551	496	1.15	0.56	3.77	5.48	12.9	90.5	3630
21	Producer gas (buckwheat anthracite)	8.0	0.1	50.0	23.2	17.7	1.0	....	....	.....	0.86	1.06	143	133	0.22	0.32	1.34	1.88	19.4	70.5	3040
22	Producer gas (bituminous)	4.5	0.6	50.9	27.0	14.0	3.0	....	....	....	0.86	1.23	163	153	0.23	0.35	1.48	2.06	18.9	74.6	3175
23	Producer gas (0.6 lb steam per lb coke)	6.4	....	52.8	27.1	13.3	0.4	....	....	....	0.88	1.00	135	128	0.17	0.34	1.32	1.82	20.5	70.3	3010
24	Blast-furnace gas	11.5	....	60.0	27.5	1.0	.....	....	....	....	1.02	0.68	92	92	0.02	0.39	1.14	1.54	25.5	59.5	2650
25	Commercial butane	(C_4H_{10} 93.0)			.....	(C_3H_8 7.0)		....	....	....	1.95	30.47	3225	2977	4.93	3.93	24.07	32.93	14.0	90.5	3640
26	Commercial propane	(C_3H_8 100.0)			.....	.....	.....	....	....	.....	1.52	23.82	2572	2371	4.17	3.00	18.82	25.99	13.7	91.2	3660

Table H-10 gives specific gravities, specific volumes, and heating values. Table H-11 gives combustion ratios for computing air and combustion properties. References to sources of these data have already been quoted in the footnotes on pages 288 and 289.

TABLE H-10.—SPECIFIC GRAVITIES, SPECIFIC VOLUMES, AND HEATS OF COMBUSTION OF GASES AND VAPORS FOR COMBUSTION CALCULATIONS

Substance	Formula	Molecular weight	Specific gravity (air = 1)		Specific volume SCF/lb		Heat of combustion					
							Btu/lb		Btu/SCF of perfect gas		Btu/SCF of actual gas	
			Perfect gas	Actual gas	Perfect gas	Actual gas	Gross	Net	Gross	Net	Gross	Net
Hydrogen	H_2	2.016	0.0696	0.0695	187.85	187.98	61,070	51,600	325	275	325	275
Methane	CH_4	16.042	0.554	0.555	23.61	23.56	23,880	21,520	1011	911	1014	914
Acetylene	C_2H_2	26.036	0.899	0.906	14.55	14.43	21,430	20,710	1473	1423	1485	1435
Ethylene	C_2H_4	28.052	0.968	0.974	13.50	13.42	21,640	20,290	1603	1503	1613	1512
Ethane	C_2H_6	30.069	1.038	1.046	12.59	12.49	22,320	20,430	1772	1622	1787	1636
Propylene	C_3H_6	42.079	1.453	1.480	9.000	8.83	21,040	19,690	2338	2188	2383	2231
Propane	C_3H_8	44.095	1.522	1.546	8.588	8.45	21,660	19,940	2522	2322	2563	2360
1-3 Butadiene	C_4H_6	54.088	1.867	1.934	7.002	6.76	20,250	19,200	2892	2742	2996	2840
Isobutylene	C_4H_8	56 105	1 937	2.008	6.750	6.51	20,760	19,420	3076	2877	3189	2968
1-Butene	C_4H_8	56.105	1.937	2.001	6.750	6.53	20,840	19,490	3087	2887	3191	2970
2-Butene, *cis*	C_4H_8	56.105	1.937	2.001	6.750	6.53	20,800	19,440	3081	2880	3185	2960
2-Butene, *trans*	C_4H_8	56.105	1.937	2.001	6.750	6.53	20,770	19,410	3077	2876	3181	2955
Isobutane	C_4H_{10}	58.121	2.006	2.066	6.516	6.33	21.250	19,630	3261	3013	3357	3101
n-Butane	C_4H_{10}	58.121	2.006	2.070	6.516	6.31	21,310	19,680	3270	3020	3377	3119
Isopentane vapor	C_5H_{12}	72.147	2.491	2.60*	5.249	5.02*	21,050	19,480	4010	3710	4194*	3881*
n-Pentane vapor	C_5H_{12}	72.147	2.491	2.61*	5.249	5.00*	21,090	19,520	4018	3718	4218*	3904*
Benzene vapor	C_6H_6	78.108	2.697	2.78*	4.848	4.70*	18,020	17,290	3717	3566	3834*	3679*
n-Hexane vapor	C_6H_{14}	86.173	2.975	3.17*	4.395	4.12*	20,940	19,400	4765	4414	5082*	4709*
Toluene vapor	C_7H_8	92.134	3.181	3.31*	4.110	3.95*	18,250	17,430	4440	4240	4623*	4413*
n-Heptane vapor	C_7H_{16}	100.20	3.459	3.76*	3.780	3.47*	20,860	19,340	5518	5116	6011*	5573*
n-Octane vapor	C_8H_{18}	114.23	3.944	4.34*	3.316	3.01*	20,780	19,270	6266	5812	6904*	6902*
Naphthalene vapor	$C_{10}H_8$	128.16	4.421	4.86†	2.955	2.69†	17,300	16,710	5854	5654	6431†	6212†
Carbon monoxide	CO	28.010	0.967	0.968	13.52	13.50	4,350	4,350	321	321	321	321
Carbon dioxide	CO_2	44.010	1.519	1.528	8.605	8.555	0	0	0	0	0	0
Hydrogen sulphide	H_2S	34.076	1.176	1.189	11.113	10.99	7,100	6,545	639	589	646	596
Sulphur dioxide	SO_2	64.06	2.212	2.235	5.912	5.85	0	0	0	0	0	0
Water vapor	H_2O	18.016	0.622	0.628*	21.02	20.82*	0	0	0	0	0	0
Ammonia	NH_3	17.032	0.588	0.596	22.23	21.91	9,668	8,001	435	360	441	365
Oxygen	O_2	32.00	1.105	1.105	11.83	11.82	0	0	0	0	0	0
Nitrogen	N_2	28.016	0.967	0.967	13.52	13.52	0	0	0	0	0	0
Atmospheric nitrogen	....	28.17	0.972	0.972	13.44	13.44	0	0	0	0	0	0
Air	....	28.966	1.000	1.000	13.074	13.069	0	0	0	0	0	0

NOTES: One standard cubic foot (SCF) is quantity of gas contained in 1 cu ft at 60°F and 30 in. of mercury. One lb mole = 378.7 SCF of a perfect gas.

Actual gas values are based on experimental gas-density measurements if available, otherwise deviation from perfect gas law is estimated.

* Substance is liquid at 60°F and 30 in. of mercury; however, it can be present as a vapor component of a gas. Gas-law deviation is based on behavior in gas mixture. This table in no case assumes deviations over 10 per cent. Because of the arbitrary nature of this correction many chemists prefer to use perfect-gas-law values for vapors.

† Naphthalene is solid at 60°F and 30 in. of mercury.

TABLE H-11.—COMBUSTION RATIOS OF THE LIGHT HYDROCARBONS AND OTHER FUEL COMPONENTS

BASIS: Perfect combustion with no excess air

Substance	Formula	SCF/SCF (perfect gas) or mole/mole combustible					Lb/lb of combustible				
		Required for combustion		Combustion products			Required for combustion		Combustion products		
		Oxygen	Air	CO_2	H_2O	N_2	Oxygen	Air	CO_2	H_2O	N_2
Hydrogen	H_2	0.5	2.382	0	1.0	1.882	7.937	34.344	0	8.937	26.407
Methane	CH_4	2.0	9.528	1.0	2.0	7.528	3.990	17.265	2.744	2.246	13.725
Acetylene	C_2H_2	2.5	11.911	2.0	1.0	9.411	3.073	13.927	3.381	0.692	10.224
Ethylene	C_2H_4	3.0	14.293	2.0	2.0	11.293	3.422	14.807	3.138	1.285	11.385
Ethane	C_2H_6	3.5	16.675	2.0	3.0	13.175	3.725	16.119	2.927	1.798	12.394
Propylene	C_3H_6	4.5	21.439	3.0	3.0	16.939	3.422	14.807	3.138	1.285	11.385
Propane	C_3H_8	5.0	23.821	3.0	4.0	18.821	3.629	15.703	2.994	1.634	12.074
Butylenes	C_4H_8	6.0	28.585	4.0	4.0	22.585	3.422	14.807	3.138	1.285	11.385
Butanes	C_4H_{10}	6.5	30.967	4.0	5.0	24.467	3.579	15.487	3.029	1.550	11.908
Pentanes	C_5H_{12}	8.0	38.114	5.0	6.0	30.114	3.548	15.353	3.050	1.498	11.805
Benzene	C_6H_6	7.5	35.732	6.0	3.0	28.232	3.073	13.927	3.381	0.692	10.224
Hexanes	C_6H_{14}	9.5	45.260	6.0	7.0	35.760	3.528	15.266	3.064	1.464	11.738
Toluene	C_7H_8	9.0	42.878	7.0	4.0	33.878	3.126	13.527	3.344	0.782	10.401
Heptanes	C_7H_{16}	11.0	52.41	7.0	8.0	41.41	3.513	15.20	3.076	1.438	11.69
Octanes	C_8H_{18}	12.5	59.55	8.0	9.0	46.05	3.502	15.15	3.084	1.420	11.65
Naphthalene	$C_{10}H_8$	12.0	57.170	10.0	4.0	45.170	2.996	12.964	3.434	0.562	9.968
Carbon monoxide	CO	0.5	2.382	1.0	0	1.882	0.571	2.471	1.571	0	1.900
Ammonia	NH_3	0.75	3.573	SO_2	1.5	3.323	1.409	6.097	SO_2	1.587	5.511
Hydrogen sulphide	H_2S	1.5	7.146	1.0	1.0	5.646	1.409	6.097	1 880	0.529	4.688

5. Natural Gasoline and Liquefied Gases

a. Units of Measurement.—Sales are usually based on gallons even though a "gallon" of a liquefied gas does not lend itself to precise definition. For this reason sales are sometimes based on standard cubic feet (of vapor) as in the case of gases.

When sales are on the gallon basis, the analysis is customarily expressed as liquid volume per cent computed on the basis of standard values of liquid densities assumed to be the same for a given component at 60°F, regardless of the pressure and composition of the mixture.

b. Properties of Component Hydrocarbons.—Data are given in Table H-12. The melting point, freezing point, liquid densities, and heats of vaporization at 1 atm pressure are based on the California

Natural Gasoline Association table.[1] The heats of vaporization at 60°F are from various sources (or estimated), and the heats of combustion are computed from those given in Table H-10. Vapor pressures were taken from the Natural Gasoline Association of America table.[2] Vapor equivalent to 1 gal was computed from the liquid densities and the specific volume (Table H-10).

As combustion ratios of a liquefied hydrocarbon are identical with those for its vapor, Table H-11 may be used without change.

TABLE H-12.—PROPERTIES OF LIGHT HYDROCARBONS

Substance	Formula	Molecular weight	Melting point, °F	Boiling point at 1 atm, °F	Liquid density, lb/gal	Heat of combustion, Btu/gal		Heat of vaporization, Btu/lb		Vapor pressure at 100°F, psi	Vapor from 1 gal	
						Gross	Net	At boiling point	At 60°F		SCF of perfect gas	SCF of actual gas
Methane*.........	CH_4	16.042	−296.5	−258.5	(2.5)*	(59,420)	(53,520)	245	(110)*	.....	59.02	58.90
Ethylene*.........	C_2H_4	28.052	−272.6	−154.7	(3.3)*	(70,920)	(66,460)	208	(150)*	.....	44.55	44.29
Ethane*..........	C_2H_6	30.069	−297.8	−128.2	(3.3)*	(73,160)	(66,920)	211	(150)*	.....	41.55	41.22
Propylene.........	C_3H_6	42.079	−300.8	−54.0	(4.2)	87,740	82,060	189	154	228	37.80	37.09
Propane..........	C_3H_8	44.095	−305.8	−43.8	4.239	91,180	83,900	183	153	189.5	36.40	35.82
Isobutylene.......	C_4H_8	56.105	−221.3	+19.4	5.040	103,820	97,070	172	162	63	34.02	32.8[illegible]
1-Butene........	C_4H_8	56.105	−319.0	20.4	5.001	103,420	96,670	174	164	66	33.76	32.56
2-Butene, *cis*....	C_4H_8	56.105	−218.7	38.7	5.118	105,530	98,570	187	(182)	.....	34.55	33.42
2-Butene, *trans*..	C_4H_8	56.105	−158.4	33.7	5.118	105,380	98,420	183	(178)	.....	34.55	33.42
Isobutane.........	C_4H_{10}	58.121	−229.0	10.0	4.697	99,110	91,500	158	146	73.5	30.61	29.73
n-Butane..........	C_4H_{10}	58.121	−218.2	31.1	4.863	102,850	94,980	166	159	52.0	31.69	30.69
Isopentane........	C_5H_{12}	72.147	−257.1	82.4	5.201	108,700	100,430	146	151	20.3	27.30	26.11
n-Pentane.........	C_5H_{12}	72.147	−201.5	97.0	5.251	110,060	101,760	153	160	15.5	27.56	26.26
Benzene..........	C_6H_6	78.108	+41.9	176.2	7.344	131,750	125,660	170	184	.....	35.60	34.52
n-Hexane.........	C_6H_{14}	86.173	−139.9	155.7	5.526	114,830	106,320	146	....	6.1	24.29	22.76
Toluene...........	C_7H_8	92.134	−139.2	230.9	7.244	130,900	124,230	156	....	.....	29.77	28.61
n-Heptane........	C_7H_{16}	100.2	−131.4	209.1	5.727	118,550	109,840	138	....	1.6	21.65	19.87
n-Octane..........	C_8H_{16}	114.2	−70.2	258.1	5.885	121,350	112,460	131	....	0.5	19.51	17.71

* Pure methane and ethylene do not exist as liquids at 60°F. Values given are intended to represent those of their solutions in hydrocarbon mixtures. Pure ethane does exist as a liquid of density of 3 lb/gal. The values given intend to represent properties in dilute solutions.

c. Vapor Pressure and Storage.—The vapor pressure of natural gasoline is customarily determined by the Reid apparatus. The

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[1] See footnote, p. 289.

[2] See footnote, p. 288.

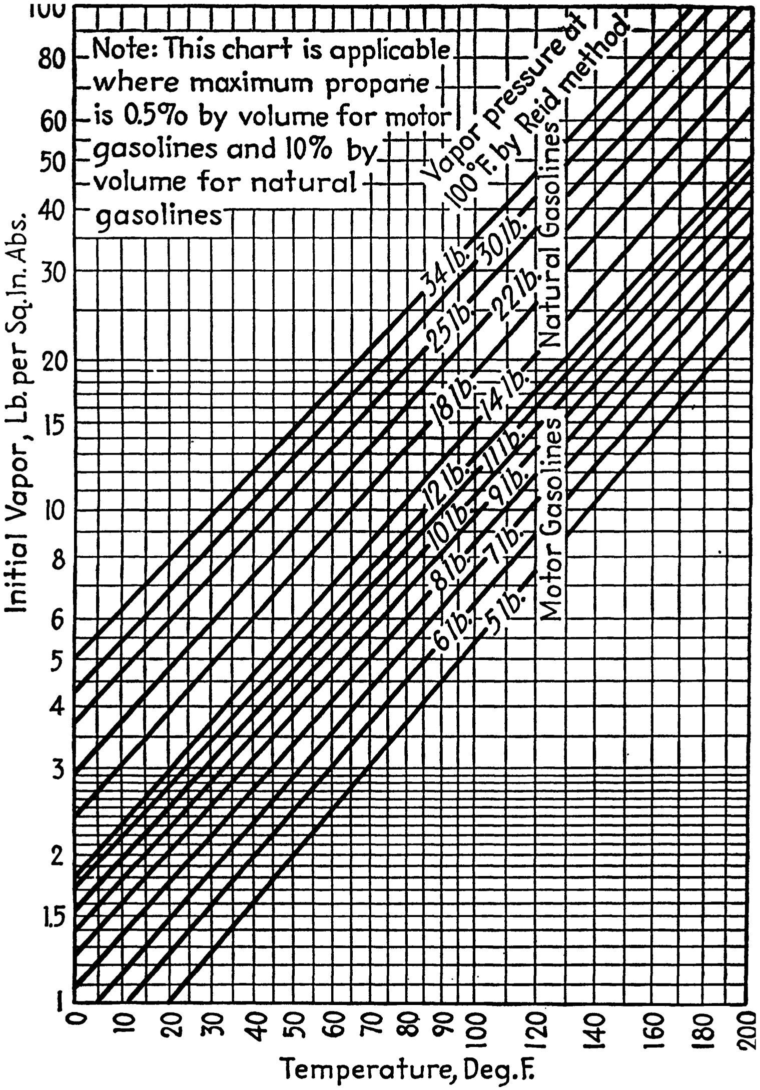

FIG. H-5.—Vapor pressures of motor and natural gasolines. (*By permission, Chicago Bridge & Iron Company.*)

resulting Reid pressure is closely related to the true vapor pressure, but not identical owing to inadequacies of the test. Figure H-5 gives the approximate relation to the true vapor pressure and also permits estimation of vapor pressures over a range in temperature.

Where the vapor pressure is not known, approximate values may be obtained from the vapor pressures of components and Raoult s law—or better from vaporization constants (see Chapter L).

The Natural Gasoline Association of America[1] recommends storage pressures based on vapor-pressure data as follows:

$$SP = FP + (14.7 - IP)\frac{FT}{IT} - 14.7$$

where SP = storage pressure, psig
FP = vapor pressure of liquid at maximum surface temperature, psia
IP = vapor pressure of liquid at minimum surface temperature, psia
FT = maximum absolute temperature in vapor space, °R
IT = minimum absolute temperature in vapor space, °R

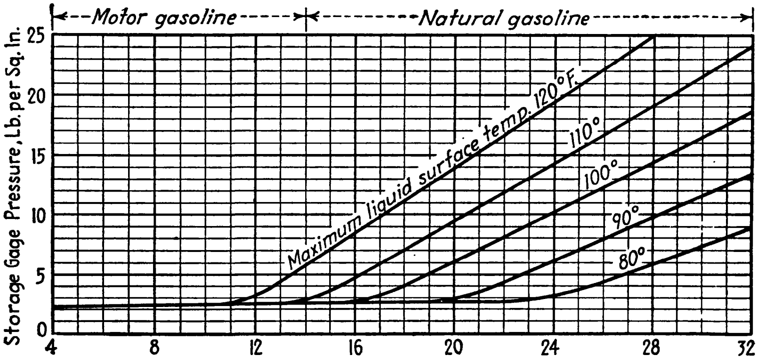

FIG. H-6.—Graph showing storage pressure required to prevent standing losses from volatile products. (*"Technical Manual," Natural Gasoline Supply Men's Association, Tulsa,* 1941.)

The storage pressure may be more simply determined by Fig. H-6 which is based on the above relation and the assumptions listed below:

1. Minimum surface temperature 10°F less than maximum liquid surface temperature.
2. Maximum vapor space temperature 40°F greater than maximum liquid surface temperature.
3. Minimum vapor space temperature 15°F less than maximum liquid surface temperature.

These assumptions are extreme and lead to higher storage pressures than are frequently required.

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[1] See footnote, p. 288.

TABLE H-13.—HEAT DISTRIBUTION
(Haslam and Russell, "Fuels and Their Combustion,"

	Boiler	Gas producer	Blue water gas set	Carbureted water gas set	Oil gas set	Coke oven
1. Heat input (per cent of total heat):						
(a) Potential heat in fuel	91.9	96.3	93.3	Coal 57.3 Oil 38.5	96.7	Coal 92 8 Gas 7.2
(b) Heat in auxiliaries (air and steam)	0.0	2 7	6.7	4.1	3.0	0.0
(c) Heat in raw materials	8.1	0.0	0.0	0.0	0.0	0.0
Total	100.0	100.0	100.0	100.0	100.0	100.0
2. Heat output.						
(a) Heat in product	71.2	72.7	49.9	60.2	42.8	87.5
(b) Heat absorbed in reactions	.. ..	....	.....	....	....	....
(c) Furnace efficiency	71.2	Hot 90 2 Cold 72.7	49.9	60.2	42 8	87.5
(d) Heat losses, total	28 8	Hot 9.8 Cold 27.3	50.1	39.8	57.2	12.5
(1) Stack loss	21.0	Sensible heat in producer gas 17.5	39.2	19.2	7.2	2.3
(2) Cinder loss	3.9	1.7	7.0	4.0	0.0	....
(3) Radiation loss	3.9	8.1	3.9	3.7	1.4	1.2
(4) Unaccounted-for losses					1 3	2.5
(5) Cooling water loss	.....	....	.. ..	....	. . .	....
(6) Miscellaneous Accounted-for losses	.....	....	.....	....	Potential heat in carbon 9.5 Potential heat in tar 3.1	Sensible heat in coke 4.1 Sensible heat in gas 2.2 Sensible heat in tar 0.2
Remarks	.....	....	.....	....	Potential heat in lamp-black 26 2 Other losses 8.5	

6. Combustion Data and Calculations for Fuels in General

a. Definitions of Heating Value.—There are two common heating values in use: net and gross. The difference between these values arises because one product of combustion, water, is produced as a vapor on burning the fuel but is condensed to liquid on recooling to room temperature.

The net heating value of a fuel is defined as the heat produced on combustion of the fuel at any given temperature (usual practice, 60°F) and assuming that the products of combustion are cooled back to the

IN INDUSTRIAL FURNACES
McGraw-Hill Book Company, Inc., New York, 1926)

Blast furnace	Open-hearth furnace	Billet furnace		Rotary cement kiln	Rotary lime kiln	Shaft lime kiln, producer gas fired	Down-draft brick kiln	Tunnel kiln continuous	Tunnel kiln Dressler	Ring-type brick kiln	Blast-furnace stove
		Non-continuous	Continuous with recuperator								
93.1	95.0	100.0	100.0	100.0	100.0	95.9	100.0	100.0	100.0	100.0	100.0
6.8	0.0	0.0	0.0	0.0	0.0	4 1	0.0	0.0	0.0	0.0	0.0
0.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100 0	100.0	100.0
8.2	Steel 21.6 Slag 3.1	25.0	52.5	14.1	12.3	12.0	23.7	17.2	67.2	51.5	62.0
28.4	−7.9	......	.....	22.4	28.4	35.0	2.7	7 9	0.0	0.0	0.0
36.6	11.8	25.0	52.5	22.4	28.4	35.0	26.4	25.1	67.2	51.5	62.0
63.4	88.2	75.0	47.5	77.6	71.6	65.0	73.6	74.9	32.8	48.5	38.0
55.0	62.0	40.0	29.3	48.3	41.2	30.6	33.3	27.9	8.3	38.2	18.6
6.1											
.....	....	2.0	.....	.....	.....	0.7	0.0	3.3			
0.3	21.2	27.0	16.1	15.2	7.9 10.2	12.4	40.3	43.7	5.4	10.3	10.1
2.0	....	4.0	2.1	.....	.....	4.7	.....	.....	......	.....	2.6
.....	....	Heat in slag 2.0	.....	.....	.....	Loss in producer gas main 4.6	.....	.....	Heat in trucks 19.1	.....	6.7
Potential heat in blast-furnace gas is not a real loss because later used						Over-all balance including producers and kiln					

initial temperature, the water vapor being uncondensed.[1] The gross heating value of a fuel is defined as the total heat developed after the products are cooled back to the starting point, assuming that all of the water is condensed.[1]

In practice, neither heating value can be experimentally realized. A combustion calorimeter does cool the burned gases to nearly the original temperature, condensing most of the water and thus approximating closely the gross heating value as just defined. The differences due to uncondensed water vapor saturating the fixed gases and to solubility of gases in water are cause of concern to the thermochemist but need not concern us here. In actual furnaces the combustion products leave the stack without condensation of water vapor, so that the net heating value is closer to the heat realized by industrial use.

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[1] "Combustion," 3d ed., American Gas Association, New York, 1932, *cf.* A.S.T.M., Tentative Standard, D 407-35T, for more precise definitions.

Since both heating values are essentially arbitrarily defined, it follows that choice between the two is largely one of taste. The net heating value is preferred by many European workers, whereas the use of gross heating values is more common to American practice and will be used for most purposes in this book. The units of heat used here are the British thermal unit (Btu) and the therm (100,000 Btu).

b. Excess Air and Furnace Losses.—Table H-13, pages 296–297, presents the heat distribution for several types of combustion equipment. It will be noticed that the stack loss is, in general, the most important item, though other losses frequently are of the same importance.

The stack loss is determined to some extent by the fuel employed, but to a greater extent by the temperature and the quantity of excess air. Figure H-7, or by the equation given with it, permits estimation of the quantity of excess air when carbon monoxide, carbon dioxide, sulphur dioxide, water vapor, oxygen, and nitrogen are the sole components of the stack gas, and the fuel is itself free from nitrogen. The relatively small nitrogen content of typical fuels (except, perhaps, producer gas) does not, in practice, impair the calculations. Other components are rarely present unless a deficiency of air is employed. Flue gases high in carbon monoxide may, however, also contain some unburned hydrogen and hydrocarbons resulting from local deficiencies of oxygen, particularly if the distribution of air to the burners or to various parts of coal bed is not uniform.

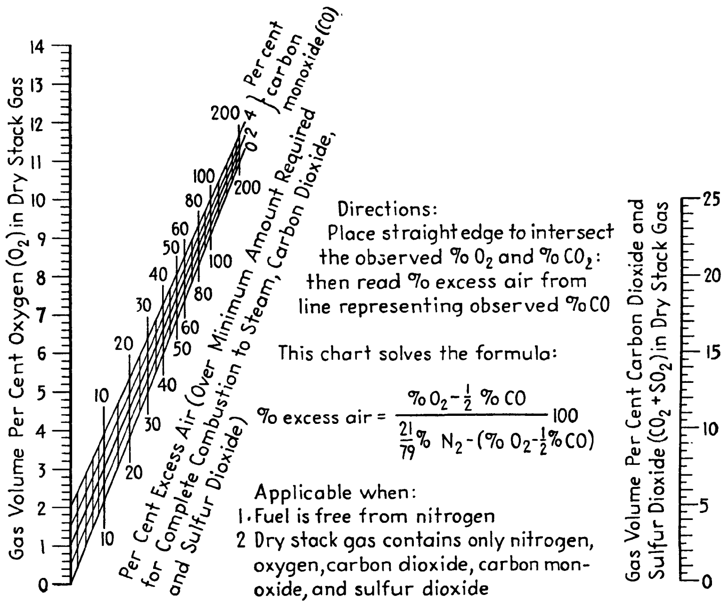
For a given fuel of constant known composition, the excess air may be computed from either the oxygen or carbon dioxide content of the stack gas. This result is more accurate if based on oxygen, but carbon dioxide is usually more convenient especially if a carbon dioxide recorder is available. Excess may be computed by the following formula:

$$E = 7900 \frac{b - a}{a(100 - b)}$$

where E = per cent excess air
a = per cent CO_2 (+ CO, if also present)
b = ultimate per cent CO_2 for perfect combustion (values for commercial gases are given in Table H-9)

Actually this is only one method of estimating. Others are illustrated in Examples H-1 to H-3. Figures H-8 to H-14 permit rapid estimation of stack losses for different fuels as follows:

Bituminous coal	Fig. H-8
Coke	Fig. H-9
Producer gas	Fig. H-10
Coke-oven gas	Figs. H-11 and H-12
Natural gas	Fig. H-13
Various gases	Fig. H-14



Directions:
Place straightedge to intersect the observed % O_2 and % CO_2: then read % excess air from line representing observed % CO

This chart solves the formula:

$$\%\text{ excess air} = \frac{\%O_2 - \frac{1}{2}\%CO}{\frac{21}{79}\%N_2 - (\%O_2 - \frac{1}{2}\%CO)}\,100$$

Applicable when:
1. Fuel is free from nitrogen
2. Dry stack gas contains only nitrogen, oxygen, carbon dioxide, carbon monoxide, and sulfur dioxide

FIG. H-7.—Excess air from stack-gas analysis.

These charts permit the direct computation of losses and excess air from the per cent of carbon dioxide in stack gas and stack temperature. The accuracy will, however, be improved if the excess air is estimated independently either from Fig. H-7 or by algebraic methods. This is particularly true if the composition of fuel differs from those on which the chart is based. For high accuracy or for fuels not covered by the charts, direct computation is required. Methods are illustrated in Examples H-2 and H-3.

Theoretically, the maximum furnace efficiency is highest when a minimum of excess air is employed. Practical difficulties in securing close regulation of air may, however, dictate a large amount of air to ensure excess air at all times and throughout the furnace, particularly when the air flow is subject to the vagaries of natural draft. In forced-draft installation regulation is easier. Also gas burners can be regulated fairly closely even with natural draft, *provided* a draft break is employed between the furnace flue and the stack. Excess air is frequently employed to reduce the flame temperature (see discussion under that heading) and permit the use of cheaper refractories or avoid the need for water-cooled walls. In some metallurgical and ceramic

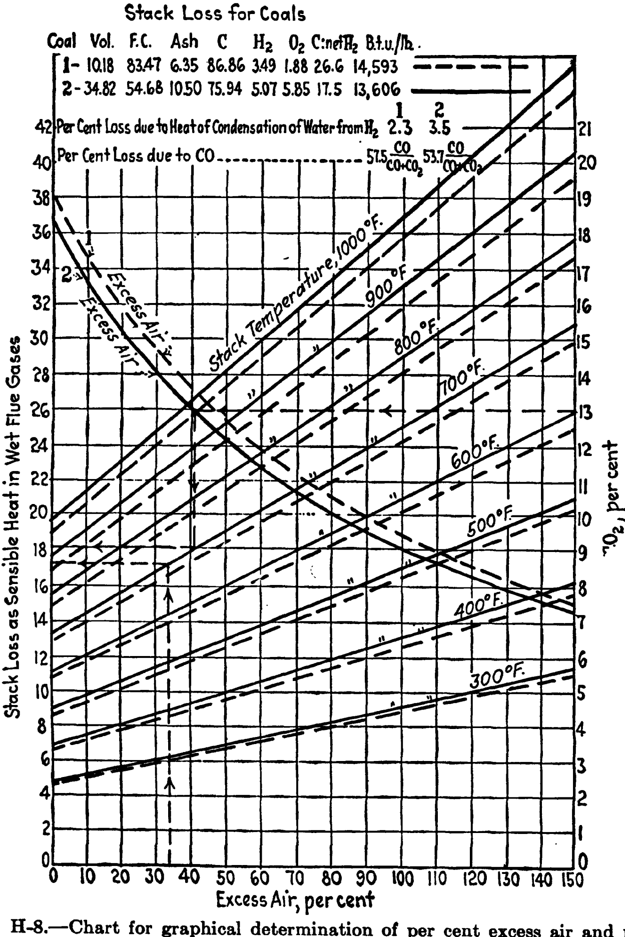


FIG. H-8.—Chart for graphical determination of per cent excess air and per cent stack loss in a furnace fired with a high-volatile or low-volatile bituminous coal. (*Haslam and Russell, "Fuels and Their Combustion," McGraw-Hill Book Company, Inc., New York,* 1926.)

furnaces the need for a controlled oxidizing or reducing atmosphere dictates the quantity of air employed. For one or more of these reasons excess air ranges from small to over 100 per cent excess air in practice. Unfortunately, no simple rule is available to cover the wide variety of installations that may be encountered.

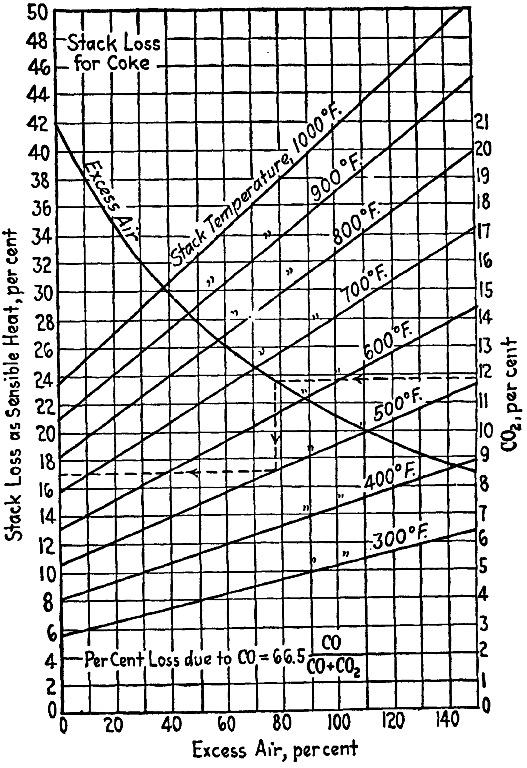


FIG. H-9.—Chart for graphical determination of per cent excess air and per cent stack loss in a coke-fired furnace. (*Haslam and Russell, "Fuels and Their Combustion," McGraw-Hill Book Company, Inc., New York,* 1926.)

In stoker-fed furnaces the cinder leaves hot, and still contains appreciable combustible material. For purposes of estimation, the cinder may be assumed to have a mean specific heat of 0.25 Btu/(°F)(lb), and the unburned material may be assumed to be carbon and to have a heating value of 14,000 Btu/lb. Estimating cinder loss is illustrated in Example H-3.

Furnace losses besides stack and cinder are largely heat leak by radiation and convection which may be estimated by standard methods of heat transfer (see Chapter G).

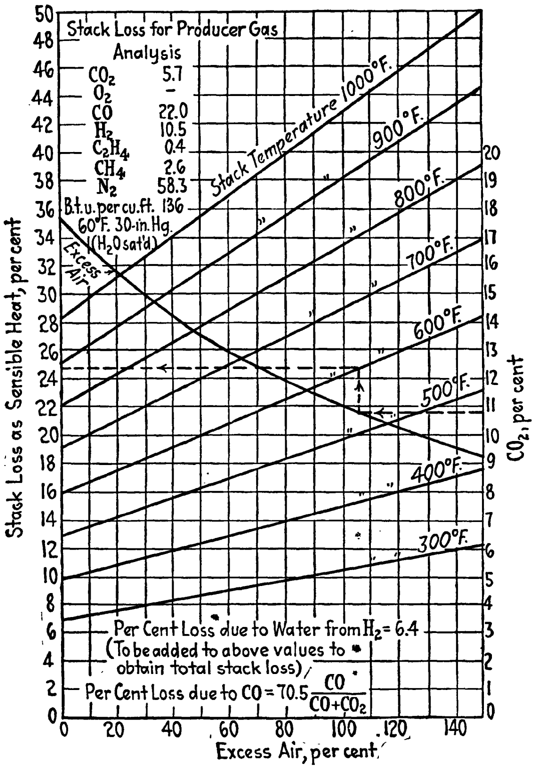


Fig. H-10.—Chart for graphical determination of per cent excess air and per cent stack loss in a furnace fired with producer gas. (*Haslam and Russell, "Fuels and Their Combustion," McGraw-Hill Book Company, Inc., New York,* 1926.)

c. Flame Temperature.—The maximum temperature of a flame depends on the nature of fuel, the quantity of air used in its combustion, and, finally, the initial temperature of fuel and air. The flame temperature is useful for estimating firebox temperatures. At these high temperatures heat conduction through furnace walls is so rapid that the surface of the brick is less than that of the flame. A refractory capable of withstanding a temperature of 300°F below the flame temperature will be satisfactory. If the furnace walls are water-cooled, this difference may, of course, be considerably greater.

Figure H-15 gives flame temperatures of Pittsburgh natural gas with various quantities of air. Table H-9 gives the flame temperature of a number of commercial gases when burned with no excess air. Figure H-16 shows the effect of preheating air and fuel. It will be noticed that the temperatures do not vary markedly and that Fig.

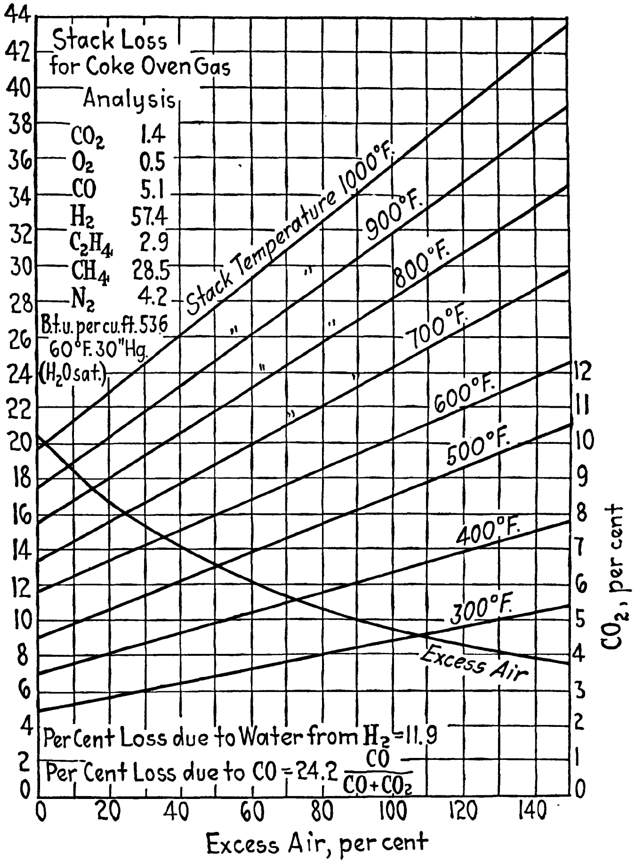


FIG. H-11.—Chart for graphical determination of per cent excess air and per cent stack loss in a furnace fired with coke-oven gas. (*Haslam and Russell, "Fuels and Their Combustion," McGraw-Hill Book Company, Inc., New York,* 1926.)

H-15 may be used for rough estimates of flame temperatures of a number of gaseous fuels.

Flame temperatures of liquid fuels would be expected to be lower than those of gaseous fuels owing to the heat used in vaporizing the fuel; however, because of the relatively higher combustion values of the heavy hydrocarbons, the difference may be small (see Example

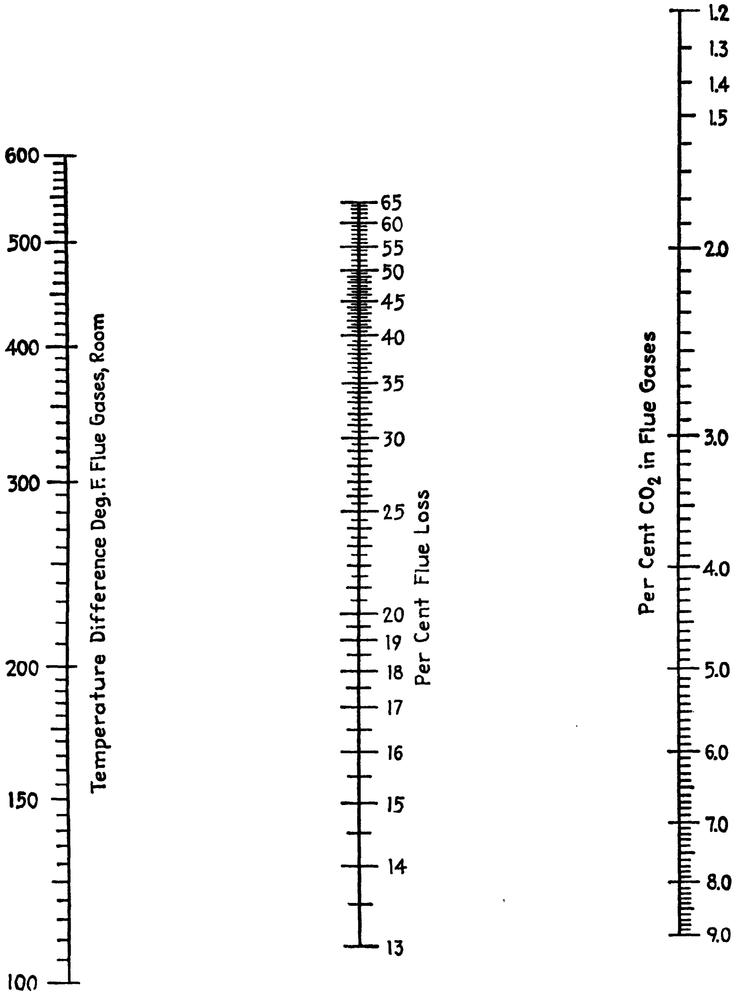


FIG. H-12.—Alignment chart for flue losses. Coke-oven gas 520 to 590 Btu/SCF ("*Fuel—Flue Gases,*" *American Gas Association, New York,* 1940.)

H-4). Flame temperatures of coal and coke are lower because of their oxygen content.

The calculation of flame temperatures is theoretical. However, calculated values have been closely approached (at least for fast-burning gases) by experimental temperatures which are but slightly lower because of small unavoidable heat losses. If no heat is lost, the heat content of the products of combustion must be equal to the heat of combustion plus the heat content of the fuel and air (or oxygen). At the high temperatures frequently involved, however, carbon dioxide and steam dissociate, oxides of nitrogen may be present, and even atomic hydrogen and oxygen may be formed. Correction for the heats of these reactions must be made, and the computations are rendered very tedious so that details of the exact method will be omitted. Persons requiring data for exact calculations may find methods out-

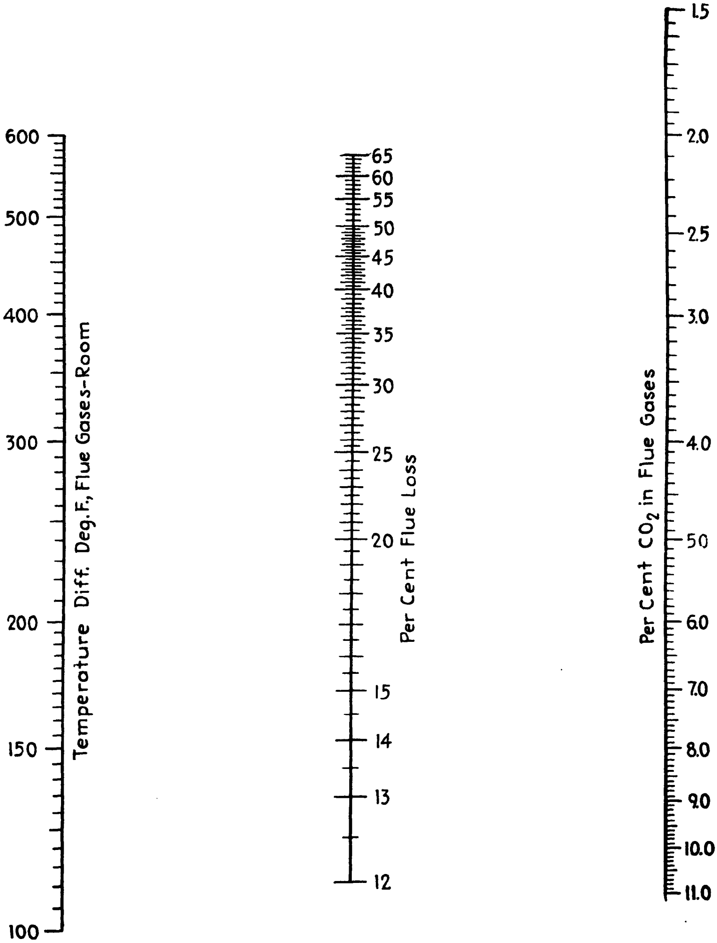


FIG. H-13.—Alignment chart for flue losses. Natural gas 1060 to 1190 Btu/SCF ("*Fuel—Flue Gases*," *American Gas Association, New York*, 1940.)

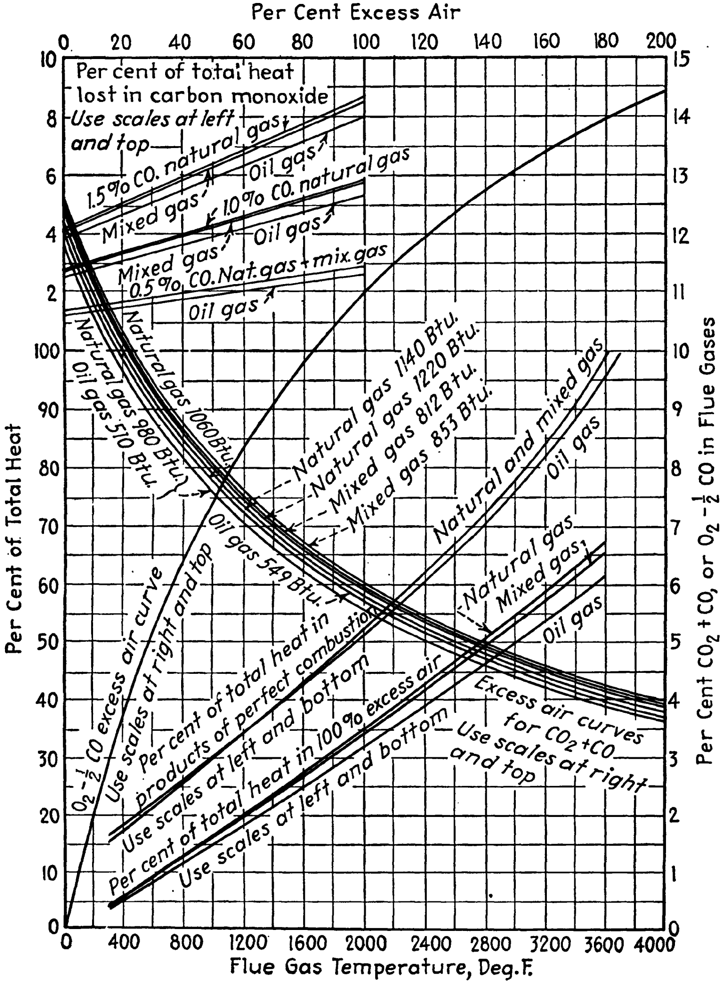


FIG. H-14.—Combustion chart for natural, mixed, and oil gases, giving heat losses for various percentages of excess-air and flue-gas temperatures. (*Graf, "Gas Engineers' Handbook," McGraw-Hill Book Company, Inc., New York,* 1934.)

lined in good texts on physical chemistry. An excellent and very readable treatment is given by the American Gas Association.[1] A very scholarly discussion based on the best thermodynamic data available has been given by Lewis and von Elbe.[2]

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[1] "Combustion," *op. cit.*

[2] *Phil. Mag,* **20,** 44 (1935); *J. Am. Chem. Soc.,* **57,** 612, 2737 (1934).

The error caused by neglect of dissociation is illustrated by the dotted line in Fig. H-15. It will be noted that, for no excess air, the discrepancy with the exact value is about 200°F and becomes negligible at 25 per cent excess air. This is due partly to the lower temperature and partly to repression of dissociation by the free oxygen contained in the excess air. Consequently it may be seen that if more than 20 per cent excess air is used, neglect of dissociation is justifiable for most process purposes, provided the temperatures are in the range of Fig.

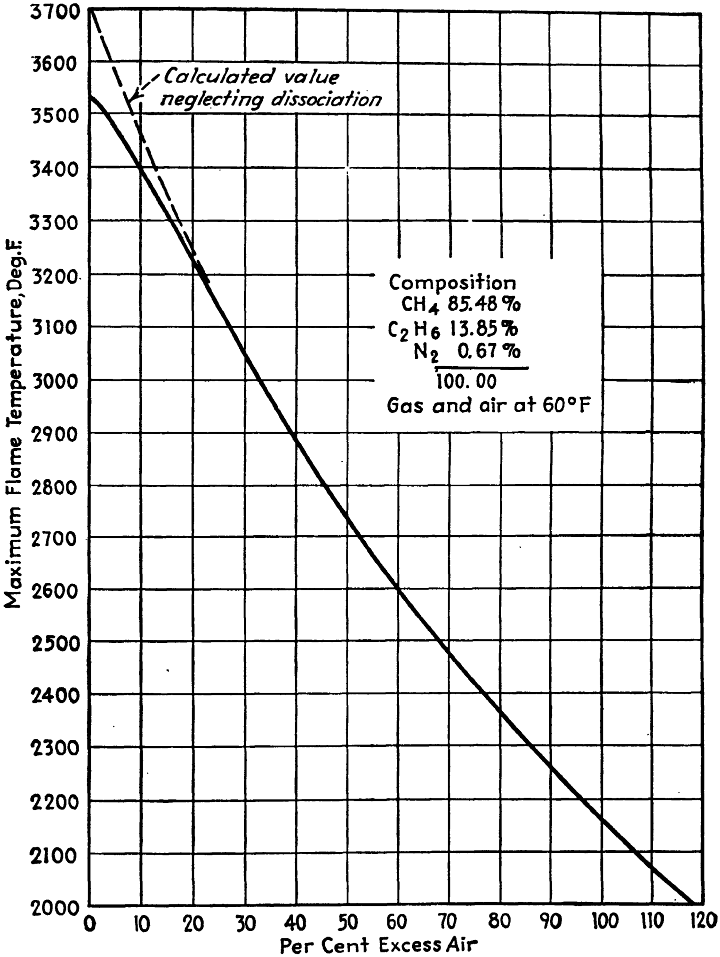

FIG. H-15.—Flame temperatures of Pittsburgh natural gas and air mixtures.

H-15. If the flame temperature is much higher because of the use of preheated air or the use of pure oxygen, this may not be true. Example H-4 gives one method of calculation of flame temperatures neglecting dissociation.

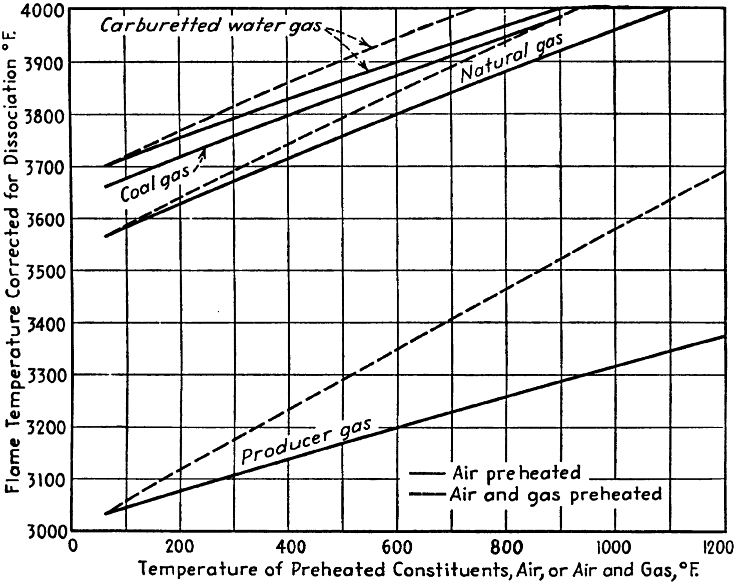

FIG. H-16.—Effect of preheat on flame temperature. ("*Combustion*," *3d ed.*, *American Gas Association*, *New York*, 1932.)

d. Illustrative Examples.—The underlying principles of combustion calculations are very simple and are outlined below.

1. Combustion reactions:
   $C + \frac{1}{2}O_2 = CO$ (incomplete combustion)
   $C + O_2 = CO_2$
   $2H + \frac{1}{2}O_2 = H_2O$
   $H_2 + \frac{1}{2}O_2 = H_2O$
   $S + O_2 = SO_2$
   $P + \frac{5}{4}O_2 = \frac{1}{2}P_2O_5$
   $C_cH_hO_oN_nS_s + (c + \frac{1}{4}h - \frac{1}{2}o + s)O_2 = cCO_2 + \frac{1}{2}hH_2O$
   $+ \frac{1}{2}nN_2 + sSO_2$
2. Material balance:
   Carbon in = carbon out
   Hydrogen in = hydrogen out
   Etc.

3. Heat balance:
   Heat in = heat out
   Heat in includes sensible heat and heat of combustion
   Heat out includes sensible heat and heat of combustion of unburned material; also includes latent heat of water vapor if gross heat of combustion is used

These principles together with data on fuels (such as given in earlier sections of the chapter and in Chapter E) permit computation of heat losses, fuel and air required to supply needed heat, flame temperature heat losses, and similar problems. Methods of application are probably better shown by illustrations than by abstract discussion. Five examples follow.

Example H-1. Compute the combustion products and stack-gas analysis from one pound of Knife River Lignite when completely burned with 40% excess air. Composition of this coal may be taken from Table H-2.

SOLUTION:

1. Weight of ash- and moisture-free coal (lignite),

% moisture	35.6
% ash	5.6
Total	41.2

Ash- and moisture-free coal = 100 − 41.2 = 58.8% or 0.588 lb/lb

2. Air required (factors from Table H-4) to burn,

C: 0.588 × 0.720 × 150	63.5 SCF/lb
H: 0.588 × 0.047 × 448	12.4
O: 0.588 × 0.211 × (−56.3)	−7.0
S: 0.588 × 0.012 × 56.2	0.4
Subtotal	69.3
40% excess = 0.40 × 69.3	27.7
	97.0 SCF/lb

3. Nitrogen in flue gas,

From air = 0.79 × 97.0	76.6 SCF/lb
From fuel = 0.588 × 0.010 × 13.5	0.1
Total	76.7

4. Oxygen in flue gas,

Oxygen in excess air = 0.21 × 27.7	5.82

5. Carbon dioxide in flue gas,

$0.588 \times 0.720 \times 31.4$ 13.3

6. Sulphur dioxide in flue gas,

$0.588 \times 0.012 \times 11.7$ 0.08

7. Flue products exclusive of water vapor,

Total of items 3 to 6 .... 95.9

8. Composition of dry stack gas,

$\% (CO_2 + SO_2) = 100 \frac{13.3 + 0.08}{95.9}$ 14.0

$\% O_2 = 100 \frac{5.82}{95.9}$ 6.1

$\% N_2 = 100 \frac{76.7}{95.9}$ 79.9

Total 100.0

9. Water vapor in flue gas,

From burning H,

$0.588 \times 0.047 \times 189$ .... 5.2 SCF/lb

From moisture in coal,

0.356×21.02 .... 7.5

Total .... 12.7 SCF/lb

10. Total flue products,

Items 7 and 9 = 108.6 SCF/lb of coal

Example H-2. A furnace is fired with Los Angeles natural gas of composition given by Table H-9. The stack temperature is 620°F, and the stack gas is 9.1 % CO_2, 0.0 % CO, and 6.1 % O_2. Find the per cent gross heating value lost as heat content of stack gas (stack loss).

SOLUTION:

1. Stack products from 1 SCF of fuel excluding excess air (data from Table H-9),

N_2	7.94 SCF/SCF
CO_2	1.16
Subtotal	9.10
H_2O	2.10
Total	11.20 SCF/SCF

2. Excess air computed from % CO_2,

Let x = SCF excess air/SCF of fuel.

$$\% CO_2 = 100 \frac{1.16}{9.10 + x} = 9.10$$

$$9.10 + x = \frac{116}{9.1} = 12.75$$

$$\text{Excess air} = 12.75 - 9.1 = 3.65 \text{ SCF/SCF of fuel}$$

$$\left(\% \text{ excess air} = 100 \frac{3.65}{10.05} = 36.3\%\right)$$

3. Excess air computed from % O_2,

Flue gas contains 6.1% O_2, or 6.1/0.21 = 29.0% air.

$$\text{Volume of excess air} = \frac{29}{100 - 29} 9.10 = 3.72 \text{ SCF/SCF of fuel}$$

(% excess air $= 100 \frac{3.72}{10.05} = 37.0\%$, and this value agrees with that computed from % CO_2)

4. Total combustion products,

Use excess air as computed from % O_2.

Total $N_2 = 7.94 + 0.79 \times 3.72 = 7.94 + 2.94$.... 10.88 SCF

$O_2 = 0.21 \times 3.72$........................ 0.78 SCF

(CO_2, H_2O from item 1)

5. Heat content of flue products,

Gas	SCF	Btu/SCF (from Fig. E-10)	Btu
N_2	10.88	10.4	113.1
O_2	0.78	10.8	8.4
CO_2	1.16	15.1	17.5
H_2O	2.10	12.3	25.8
Total sensible heat above 60°F			164.8 Btu/SCF fuel
Latent heat,			
H_2O	2.10	50.36	105.6
Total heat content above 60°F			270.4 Btu/SCF fuel

This is the stack loss.

6. % stack loss, $100 \frac{270.4}{1073} = 25.2\%$

Example H-3. Find the quantity of coal required for firing a calcining kiln. The heat required for the calcining process is 4,500,000 Btu/hr. The coal to be used is very similar to the Lower Freeport coal listed in Table H-2. From similar type installations, using a different coal, it was found that (1) the stack analysis was 11.0% CO_2, 1.2% CO, and 6.6% O_2; (2) the stack temperature was 800°F; (3) the cinder contained 22% combustible; and, (4) heat loss by radiation, convection, and miscellaneous factors was about 8% of the heating value of the fuel.

SOLUTION:

Method: Find heat supplied per pound of coal and from this the amount required.

1. Heating value of coal = 14,310 Btu/lb
2. Cinder formed from 1 lb coal,

   Ash content = 0.064 lb

$$\text{Total cinder formed} = \frac{0.064}{1 - 0.22} = 0.082 \text{ lb}$$

Combustible left in cinder = 0.22 × 0.082 = 0.0180 lb

3. Cinder loss per pound of coal,

Sensible heat (at 1000°F) = 0.082 × (1000 − 60) × 0.25 (taking specific heat as 0.25)	19 Btu/lb
Heat of combustion = 0.018 × 14,000	252
Total loss	271 Btu/lb

or

$$100 \frac{271}{14{,}310} = 1.9\%$$

4. Combustible material per pound of coal,

Ash	0.064 lb
Moisture	0.020
Total	0.084

Ash- and moisture-free coal = 1 − 0.084 = 0.916 lb.

C = 0.916 × 0.886*	0.812
H = 0.916 × 0.053	0.048
O = 0.916 × 0.038	0.035
N = 0.916 × 0.015	0.014
S = 0.916 × 0.008	0.007
Total	0.916

* 0.886 = % C/100, etc.

Carbon actually burned,

$$0.812 - 0.018 = 0.794 \text{ lb/lb coal}$$

5. Products of perfect combustion per pound of coal excluding excess air,

CO_2 from C = 0.794 × 31.38.................. 24.9 SCF/lb
H_2O from moisture = 0.020 × 21.02...... 0.42
H_2O from H = 0.048 × 188.7............ 9.05
Total water vapor.......................... 9.5
SO_2 from S = 0.007 × 11.69.................. 0.1

Nitrogen from

C = 0.794 × 118.5.................... 94.1
H = 0.048 × 353.6.................... 16.9
N = 0.014 × 13.5..................... 0.2
S = 0.007 × 44.4..................... 0.3
Subtotal.......................... 111.5
Less credit for oxygen in coal,
−0.035 × 44.5.... −1.5
Total nitrogen............................ 110.0
Total products of combustion............... 144.5

(Factors used above are from Table H-4, except specific volume of steam, which is from Table H-10.)

6. Correction for carbon monoxide,

$CO_2 + CO + SO_2 = 24.9 + 0 + 0.1 = 25.0$ SCF/lb coal (result of 5)

If CO in the proportion represented by 1.2% CO and 11.0% CO_2,

CO formed $= 25.0 \dfrac{1.2}{11 + 1.2}$ .... 2.4 SCF/lb coal
Leaving $CO_2 + SO_2 = 25 - 2.4$............ 22.6 SCF/lb coal

Nitrogen produced in combustion of CO

= 1.9 SCF/SCF of CO (Table H-11)

or

$1.9 \times 2.4 = 4.6$ SCF/lb coal

This nitrogen was included in calculation 5 but should be omitted as the CO was not actually burned.

Corrected flue products are then,

$N_2 = 110.0 - 4.6 = 105.4$ SCF/lb coal
Total $= 144.5 - 4.6 = 139.9$
$H_2O = 9.5$

Exit stack gas, dry basis $= 139.9 - 9.5 = 130.4$ SCF/lb

7. Excess air,

Let y = SCF of excess air/lb of coal

$0.21y$ = SCF of excess oxygen/lb of coal

$$\% \ O_2 = 6.6 = 100 \frac{0.21y}{130.4 + y}$$

$$861 + 6.6y = 21y$$

$$14.4y = 861$$

$$y = 59.8 \text{ SCF/lb coal}$$

Oxygen = 0.21 × 59.8	12.6 SCF/lb
Nitrogen = 0.79 × 59.8	47.2
Total	59.8 SCF/lb

8. Total products of combustion including excess air,

	SCF/lb	%
$CO_2 + SO_2$ (from calculation 6)	22.6	11.9
CO (from calculation 6)	2.4	1.3
O_2 (from calculation 7)	12.6	6.6
$N_2 = 47.2 + 105.4$ (from 6 and 7)	152.6	80.2
Subtotal	190.2	100.0
H_2O	9.5	
Total	199.7	

It will be noted that the % CO_2 and CO do not quite agree with the stack-gas analysis given. This is not surprising in view of inaccuracies of gas analyses and the difference between this coal and the one previously used.

9. Stack loss per pound of coal,

Sensible heats (from Fig. E-11) at 800°F.

	Btu/SCF	SCF	Btu
$CO_2 + SO_2$	20.6	22.6	466
CO	13.9	2.4	33
O_2	14.5	12.6	183
N_2	14.0	152.6	2,136
H_2O	16.4	9.5	156
Subtotal	.....	.....	2,974
Condensing water	50.4	9.5	479
Subtotal	.....	.....	3,453
Combustion of CO	321	2.4	771
Total	.....	.....	4,224

10. Total losses and heat supplied per pound of coal,

	Btu/lb coal	% of heating value
Cinder	271	1.9
Stack	4,224	29.6
Heat leak, etc	1,145	8.0
Total	5,640	39.5
Heating value of coal	14,310	
Net heat supplied	8,670	

11. Coal required,

$$\text{Heat required} = 4{,}500{,}000 \text{ Btu/hr}$$

$$\text{Coal} = \frac{4{,}500{,}000}{8670} = 520 \text{ lb/hr}$$

or

$$520 \frac{24}{2000} = 6.24 \text{ tons/24-hr day}$$

Example H-4. A furnace is being converted from coal to oil. The refractories in the firebox are considered safe for a flame temperature of 2600°F. Find the minimum of excess air required to assure a flame temperature of 2600°F or below. The oil to be used has gross heating value of 17,500 Btu/lb and may be taken as 90% carbon and 10% hydrogen (neglecting sulphur, oxygen, and nitrogen also present).

SOLUTION:

1. Products of perfect combustion of 1 lb of oil (factors from Table H-4),

CO_2 from C 0.90 × 31.38		28.2 SCF/lb
H_2O from H 0.10 × 188.7		18.9
N_2 from C 0.90 × 118.5	106.6	
N_2 from H 0.10 × 353.6	35.4	
Total N_2		142.0
Total		189.1 SCF/lb

2. Heat content of these products at 2600°F,

Sensible heats from Fig. E-12.

	SCF	Btu/SCF	Btu/lb oil
CO_2	28.2	84.0	2,368
N_2	142.0	52.0	7,384
H_2O sensible	18.8	65.4	1,230
H_2O condensing	18.8	50.4	948
Total	.....	....	11,930

3. Heat content of air at 2600°F,

O_2 0.21×54.8	11.5
N_2 0.79×52.0	41.1
Total	52.6 Btu/SCF

4. Excess air,

Heat of combustion	17,500 Btu/lb
Less heat of products	11,930
Residue	5,570

For heat balance, this residue must equal the heat content of excess air,

$$\text{Excess air, then} = \frac{5570}{52.6} = 106.0 \text{ SCF}$$

$$\text{Air for perfect combustion} = \frac{N_2}{0.79} = \frac{142}{0.79} = 180 \text{ SCF}$$

$$\% \text{ excess air} = 100\ {}^{106}\!/_{180} = 59\ \%$$

5. Composition of stack gas,

CO_2 from calculation 1	28.2 SCF
O_2 from calculation 4 = 0.21×106	22.3
N_2 from calculation 4 = 0.79×106	83.7
N_2 from calculation 1	142.0
Total	276.2

$\% \; CO_2 = 100 \dfrac{28.2}{276.2}$	10.2
$\% \; O_2 = 100 \dfrac{22.3}{276.2}$	8.1
$\% \; N_2 = 100 \dfrac{83.7 + 142}{276.2}$	81.7
Total	100.0

Example H-5. Compute factors similar to those in Table H-4 for phosphorous.

SOLUTION:

1. Reaction,

	$4P$ +	$5O_2$ =	$2P_2O_5$
Molecular weight	30.98	32.00	141.96
No. of moles	× 4	× 5	× 2
Pounds	123.92 +	160.00 =	283.92

2. Weight ratios:

$$\text{Lb } P_2O_5/\text{lb P} = \frac{283.92}{123.92} \cdots\cdots \quad 2.2912$$

$$\text{Lb } O_2/\text{lb P} = \frac{160}{123.92} \cdots\cdots \quad \underline{1.2912}$$

$$P_2O_5 - O_2 = P \cdots\cdots \quad 1.000 \text{ (check)}$$

3. Volume of oxygen on basis of perfect gas law,

123.92 lb phosphorous = 5 moles of oxygen

or

5×378.7 SCF (from definition of standard cubic foot)

$$\text{SCF oxygen/lb P} = \frac{5 \times 378.7}{123.92} = 15.280$$

4. Volume of air and nitrogen,

Take air as 21% O_2, 79% N_2.

$$\text{Air} = \frac{15.280}{0.21} = 72.76$$

$$\text{Nitrogen} = 72.76 \times 0.79 = 57.48$$

Check: $O_2 + N_2 = 57.48 + 15.28 = 72.76$

5. Weight of air,

1 lb air = 13.074 SCF of perfect gas.

$$\text{Weight air} = \frac{72.76}{13.074} = 5.56 \text{ lb/lb P}$$

Check: Air is 23.2 weight % O_2 and weight air $= \frac{1.291}{0.232} = 5.56$ lb/lb P.

6. Weight nitrogen:

Air − oxygen = 5.56 − 1.29 = 4.27 lb/lb P

CHAPTER I

POWER

Although the process engineer is rarely required to design a power plant, he is called on to state the process utility demands in a form digestible by the power-plant engineer. This may necessitate a revision of part or all of the process to secure a balance between the various forms of heat and power that favor a low over-all cost. Information here given is intended for these purposes rather than for final power-plant design. Power and its allied subjects have been well treated by many engineers. A few useful references are given below.

Croft (rev. by Purdy), "Practical Heat," 2d ed., McGraw-Hill Book Company, Inc., New York, 1939.

Croft (rev. by Tangerman), "Steam Engine Principles and Practice," 2d ed., McGraw-Hill Book Company, Inc., New York, 1939.

Croft (rev. by Purdy), "Steam Boilers," 2d ed., McGraw-Hill Book Company, Inc., New York, 1937.

Ripper, "Steam Engine Theory and Practice," Longmans, Green and Company, New York, 1932.

Barnard, Ellenwood, and Hirshfeld, "Elements of Heat-power Engineering," John Wiley & Sons, Inc., New York, 1933.

Butterfield, Jennings, and Luce, "Steam and Gas Engineering," D. Van Nostrand Company, Inc., New York, 1938.

Craig and Anderson, "Steam Power and Internal Combustion Engines," 2d ed., McGraw-Hill Book Company, Inc., New York, 1937.

Norris and Therkelsen, "Heat Power," 2d ed., McGraw-Hill Book Company, Inc., New York, 1939.

Rudorff, "The Superheater in Modern Power Plant," Pitman Publishing Corporation, New York, 1938.

Powell, "Boiler Feed Water Purification," McGraw-Hill Book Company, Inc., New York, 1927.

Morrison, "Diesel Engineering Handbook," Diesel Publications, New York, 1940.

Anderson, "Diesel Engineering," McGraw-Hill Book Company, Inc., New York, 1938.

Von Bongart, "Diesel Engines," D. Van Nostrand Company, Inc., New York, 1938.

Creager and Justin, "Hydro-electric Handbook," John Wiley & Sons, Inc., New York, 1927.

Barrows, "Water Power Engineering," 3d ed., McGraw-Hill Book Company, Inc., New York, 1943.

A. S. M. E. Power Test Codes.

Keenan and Keyes, "Thermodynamic Properties of Steam," John Wiley & Sons, Inc., New York, 1936.

1. Boilers

a. Boiler Efficiency.—The fraction of the heating value of the fuel burned which is transferred to the boiling water is the boiler efficiency. The remainder of the heating value represents the stack loss, unburned fuel, and heat losses to air by conduction and radiation. The boiler efficiency is almost universally based on the gross heating value of the fuel. This can be realized only if the water vapor in the flue gases is condensed, as it is in an efficient calorimeter used for determining the heating values. Definitions of heating values are given in Chapter H. Blake and Purdy[1] state that sustained efficiencies of 85 to 88 per cent (for a combined boiler unit comprising boilers, economizers, and air preheaters) are common in larger central-station units but that sustained efficiencies of 80 per cent are excellent for industrial boiler plants.

Values for efficiency range from 15 to 25% for small domestic boilers used for hot water supply; from 30 to 50% for coal boilers such as would be used for hot water supply for large buildings, apartment houses, hotels, etc.; 30 to 60% for domestic and small industrial heating boilers; 40 to 70% for small power boilers, not over 50 H.P.; from 50 to 70% for moderate size boilers, up to several hundred horsepower; and from 70 to 85% for large power boilers operating under high-load factor and moderate overloads.[2]

Natural gas or oil probably gives better efficiencies in average boiler-plant installations. However, the theoretical superiority of high-rank coal is actually realized in the most efficient units. The lower rank coals give poorer efficiencies than either bituminous coal or gas.

b. Fuel Requirements.—The over-all heat requirements of a boiler unit (including economizer, if used) may be readily computed from the thermodynamic properties of steam and water. Direct calculation gives the amount of heat received by the water, and this divided by the boiler efficiency is the total supplied by fuel. This is illustrated by Example I-1.

Example I-1. Find the net heat to be supplied for generating 150,000 lb/hr of steam generated at 285 psig (300 psia) and superheated to 800°F. Make a preliminary estimate of the coal to be burned. The available coal has a heating value of 13,600 Btu/lb. 100,000 lb/hr of condensate return is available; the remainder if made up to be treated water.

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[1] Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York, 1941.

[2] From "Combustion," 3d ed., American Gas Association, New York, 1932.

SOLUTION:

1. Heating 100,000 lb/hr condensate to saturation temperature and pressure (data from Tables E-13 and E-14).

Heat content of water saturated at 300 psia	393.8 Btu/lb
Heat content of water at 170°F	137.9
Net heat	255.9

or

For 100,000 lb $\frac{100{,}000}{100{,}000} \times 255.9$ .... 255.9 therm/hr

2. Heating 50,000 lb/hr treated water to saturation temperature,

Heat content of water saturated at 300 psia	393.8 Btu/lb
Heat content of water at 70°F	38.0
Net heat	355.8

or

For 50,000 lb, $\frac{50{,}000}{100{,}000} \times 355.8$.............. 177.9 therm/hr

3. Generation of 150,000 lb of steam from saturated water,

Heat content of steam at 300 psia and 800°F	1420.6 Btu/lb (Table E-15)
Heat content of saturated water	393.8
Net heat	1026.8

or

For 150,000 lb, $\frac{150{,}000}{100{,}000} \times 1026.8$........... 1540.2 therm/hr

4. Total heat required,

Sum of above. .... 1974.0 therm/hr

5. Boiler horsepower $= \frac{1974}{0.33475}$

= 6000 (assuming no economizer employed)

6. Total heating value of fuel required

$\frac{1974}{0.70}$ = 2820 therm/hr or 67,700 therm/day

(for an assumed boiler efficiency of 70%)

7. Estimated coal consumption,

$$\frac{67{,}700 \times 100{,}000}{13{,}600} = 492{,}000 \text{ lb/day}$$

or 246 tons/day.

8. For a 350-day operating year this amounts to

$$246 \times 350 = 86{,}100 \text{ tons/yr}$$

c. Boiler Rating.—Boilers are usually rated in boiler horsepower. One boiler horsepower is 33,475 Btu/hr. Early practice was to consider 10 sq ft of heat-transfer surface equivalent to a boiler horsepower. In recent years higher boiling rates are common, and operation at 200 or 300 per cent is usual. When operated at the highest rates, the boiler efficiency may be impaired slightly and the life of the boiler tubes shortened. Nevertheless Blake and Purdy[1] suggest 250 per cent as fair industrial practice. The A.S.M.E. Power Test Codes suggest a direct *maximum* rating as thousands of Btu per hour.

d. Boiler Feed Water.—The proper treatment of the boiler water is very important for both boiler performance and life. Calcium and magnesium sulphates and acid carbonates deposit boiler scale, which impairs efficiency and endangers tubes by possibility of overheating. Even though these constituents are removed by precipitation (by lime, other reagents, or zeolites), the water may still be hazardous because of the so-called "caustic embrittlement." This embrittlement is favored by sodium hydroxide, carbonates, and silicates but retarded by sodium sulphate and certain organic materials, such as quebracho.[2] In short, a careful analysis of the available water supply should be made and submitted to a qualified expert for recommendations regarding proper treatment. This is particularly true for boilers in the higher pressure ranges.

e. Dowtherm Boilers.—The use of Dowtherm (several types are supplied by the Dow Chemical Co.) as a medium of heat transfer has become common practice. The boilers are similar in design to steam boilers. (A small amount of fixed gas is liberated on use of Dowtherm so that a vent must be provided in the return lines.) Data on these boilers are readily obtainable from licensed manufacturers.

f. Boiler Auxiliaries.—The use of air preheaters in industrial plants is not very common unless powdered coal is employed as a fuel. To some extent air preheaters, stokers, and oil and gas burners are discussed under Combustion in Chapter H. Pumps and blowers are treated in Chapters J and K, respectively.

The recovery of heat from waste gas from steel mills, glass works, or exhaust from diesel or gas engines may be accomplished by waste-heat boilers, provided the gas is available at a sufficiently high temperature, say 1000°F or over. The exit temperature is usually reduced to 300 or 500°F. Forced draft is nearly always required to secure sufficiently good heat-transfer rates. Table I-1 gives data on waste-heat boilers operating on exhaust from diesel engines.

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[1] Perry, *op. cit.*

[2] Schroeder, Berk, and O'Brien, various papers in the *Trans. Am. Soc. Mech. Engrs.* from 1934 on.

Economizers for preheating the water by the flue gas are usually included in very large central-station units but very frequently omitted in small industrial units to obviate the need for induced draft. The equipment manufacturer should be consulted.

TABLE I-1.—WASTE-HEAT BOILER PERFORMANCE ON DIESEL ENGINE EXHAUST (Perry, Chemical Engineers' Handbook, 2d ed., McGraw-Hill Book Company, Inc., New York, 1941)

Lb of steam per hr, full load; pressure 5 psi			Sq ft of heating surface	
Hp	4-cycle	2-cycle	4-cycle	2-cycle
75	77	63	72	72
100	92	78	72	72
200	154	165	72	144
300	212	229	72	144
400	327	300	144	192
500	392	370	144	240
600	483	450	192	288
700	550	525	192	336
800	638	600	240	384
900	700	675	240	432
1000	780	750	288	480

2. Steam Engines and Turbines.

a. Types of Steam Engines and Turbines.—Steam engines are classified by the number of cylinders, the valve mechanism, speed, and exhaust pressure. The simple steam engine expands steam in one stage by a single piston. Most engines are of this type. Larger engines are usually compounded, particularly if condensing. A compound engine expands steam in two or more stages, the exhaust from the first-stage cylinder drives the second-stage cylinder. Tandem compound cylinders are in line, with a common piston rod; cross compound cylinders are side by side driving separate piston rods. The principal types of valve mechanisms are slide, Corliss, nonreleasing Corliss, and Unaflow. A condensing engine exhausts at low pressures, the vacuum being secured by condensing the steam and by removal of small amounts of fixed gases in the steam by steam ejectors or vacuum pumps. Condensing engines are rather uncommon. Noncondensing engines exhaust at atmospheric pressure or above so that the exhaust may be used to supply low-pressure process-steam requirements.

Like steam engines, turbines are classified as condensing or noncondensing. In addition there is the bleeder turbine which exhausts a portion of the steam between stages to obtain exhaust steam and various pressures. Turbines are classified further according to the number and type of stages. An impulse stage operates primarily from the force of steam velocity from the steam jets. Reaction stages operate principally from the direct pressure force of the expanding steam.

The steam turbine has almost completely replaced the steam engine in large power plants, and even small electric generators are usually turbine-driven. For small units the steam engine is frequently attractive. Steam engines have a greater flexibility in regard to speed as certain "critical" velocities of turbines may have to be avoided. Bleeder turbines, on the other hand, afford the maximum flexibility as to exhaust because variable quantities of exhaust steam may be withdrawn at different pressures. For driving individual units, the choice of drive is usually determined by mechanical considerations such as the speed required and the type of motion. Turbines are ideal for driving generators, centrifugal compressors, etc. Reciprocating pumps and compressors are usually engine-driven.

The lubricating oil from a turbine or steam engine contaminates the exhaust. This oil (unless completely removed) tends to foul heat-transfer surfaces. This contamination is much less serious in the case of turbines and is sometimes a factor favoring their selection.

b. Efficiency and Steam Consumption.—The steam consumption depends not only on the inlet and exhaust conditions of the steam but also on the mechanical factors determining the relative efficiency. To simplify tabulations, a standard basis for comparing performance is desirable. The ideal steam engine (Rankine cycle) affords such a basis. This ideal engine has never been achieved but is rigorously defined by thermodynamic considerations of the maximum theoretical power developed by expansion of steam. The number of pounds of steam required to develop 1 hp-hr is called the "ideal" steam rate. Numerical values are given in Table I-2 and Fig. I-1. Steam rates of an actual engine may be obtained by dividing this ideal rate by its efficiency. This is essentially the definition of steam engine (or turbine) efficiency. Stated in other terms, the Rankine efficiency of an engine is the ratio of developed power to the power that would have been developed by the ideal engine operating under identical conditions.

Table I-3 gives *representative* data on efficiencies of steam turbines, and Fig. I-2 gives representative efficiencies of simple (single-stage) steam engines. The practical efficiencies of steam turbines are usually dictated by cost considerations. The several types of steam engines vary appreciably in efficiency, particularly with the compounding.

Table I-2.—Theoretical Steam Rates, Condensing for Engines and Turbines*

(Reprinted from "Cameron Hydraulic Data," 11th ed., 1942, by permission of Ingersoll-Rand Co.)

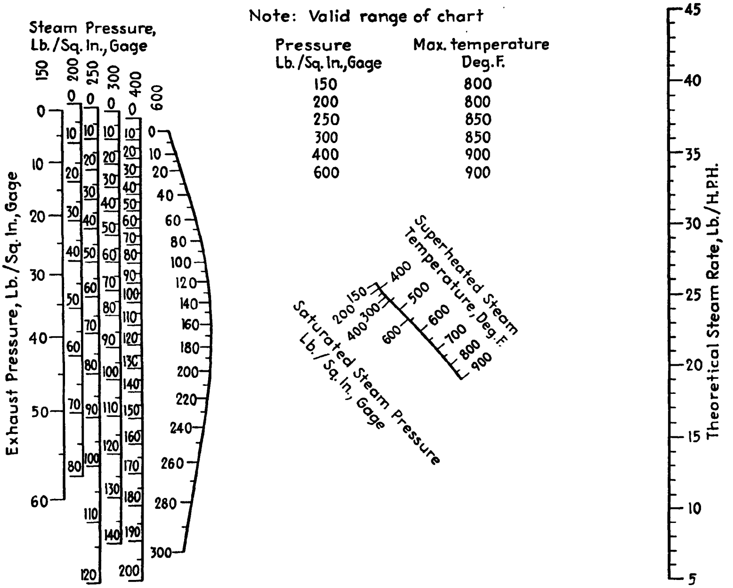
Lb per hp-hr

Initial temp., °F	Exhaust pressure, in. Hg abs				
	3.0	2.5	2.0	1.5	1.0
	150 lb gauge 365.8°F saturated steam				
365.8	8.35	8.13	7.85	7.53	7.14
400	8.17	7.95	7.67	7.36	6.90
450	7.92	7.70	7.44	7.15	6.78
500	7.67	7.45	7.22	6.93	6.68
550	7.42	7.22	6.98	6.72	6.38
600	7.18	6.98	6.76	6.51	6.18
650	6.95	6.76	6.55	6.31	6.00
700	6.72	6.53	6.34	6.11	5.82
	175 lb gauge 377.4°F saturated steam				
377.4	8.11	7.89	7.64	7.34	6.97
400	8.00	7.78	7.52	7.23	6.87
450	7.74	7.53	7.29	7.01	6.66
500	7.50	7.30	7.07	6.80	6.46
550	7.25	7.07	6.84	6.59	6.27
600	7.02	6.84	6.63	6.39	6.08
650	6.79	6.62	6.43	6.19	5.90
700	6.58	6.41	6.23	6.00	5.72
	200 lb gauge 387.8°F saturated steam				
387.8	7.92	7.71	7.46	7.19	6.84
450	7.61	7.41	7.17	6.90	6.57
500	7.35	7.16	6.95	6.68	6.37
550	7.12	6.94	6.73	6.48	6.18
600	6.90	6.72	6.52	6.29	5.99
650	6.67	6.51	6.32	6.10	5.81
700	6.46	6.30	6.12	5.91	5.64
750	6.25	6.10	5.93	5.73	5.47
	250 lb gauge 406°F saturated steam				
406.0	7.62	7.43	7.20	6.95	6.62
450	7.39	7.20	6.99	6.74	6.43
500	7.15	6.97	6.76	6.52	6.22
550	6.92	6.75	6.55	6.32	6.04
600	6.69	6.53	6.35	6.13	5.85
650	6.49	6.33	6.15	5.94	5.68
700	6.28	6.13	5.96	5.76	5.51
750	6.08	5.94	5.77	5.58	5.34

* Calculated from Keenan and Keyes, "Theoretical Steam Rate Tables," Am. Soc. Mech. Engrs., New York, 1938.

TABLE I-2.—THEORETICAL STEAM RATES, CONDENSING FOR ENGINES AND TURBINES (*Continued*)
Lb per hp-hr

Initial temp., °F	Exhaust pressure, in. Hg abs				
	3.0	2.5	2.0	1.5	1.0
	300 lb gauge 421.7°F saturated steam				
421.7	7.39	7.21	7.01	6.76	6.47
450	7.23	7.06	6.86	6.62	6.33
500	6.99	6.83	6.63	6.40	6.12
550	6.76	6.61	6.42	6.20	5.93
600	6.55	6.40	6.21	6.01	5.75
650	6.33	6.20	6.02	5.82	5.58
700	6.14	5.99	5.84	5.65	5.41
750	5.94	5.81	5.66	5.48	5.25
800	5.76	5.63	5.49	5.31	5.09
850	5.57	5.45	5.32	5.15	4.94
	400 lb gauge 448 1°F saturated steam				
448.1	7.07	6.91	6.72	6.50	6.23
500	6.78	6.63	6.46	6.25	5.98
550	6.63	6.40	6.23	6.04	5.79
600	6.34	6.19	6.03	5.84	5.60
650	6.13	5.99	5.84	5.66	5.43
700	5.94	5.81	5.67	5.49	5.26
750	5.75	5.63	5.49	5.32	5.11
800	5.57	5.45	5.32	5.16	4.96
850	5.40	5.28	5.16	5.01	4.82
	600 lb gauge 488.8°F saturated steam				
600	6.10	5.98	5.83	5.66	5.45
650	5.90	5.78	5.64	5.47	5.27
700	5.70	5.59	5.46	5.30	5.10
750	5.52	5.41	5.29	5.14	4.94
800	5.35	5.24	5.12	4.98	4.80
850	5.18	5.08	4.97	4.83	4.65
900	5.02	4.93	4.82	4.69	4.52
950	4.86	4.78	4.67	4.55	4.39
1000	4.71	4.63	4.53	4.42	4.27
	800 lb gauge 520.3°F saturated steam				
650	5.78	5.67	5.54	5.38	5.19
700	5.58	5.47	5.35	5.20	5.01
750	5.39	5.28	5.17	5.03	4.85
800	5.21	5.12	5.01	4.87	4.70
850	5.05	4.96	4.85	4.73	4.57
900	4.89	4.80	4.70	4.58	4.43
950	4.74	4.66	4.57	4.45	4.30
1000	4.60	4.53	4.43	4.32	4.18



Note: Valid range of chart

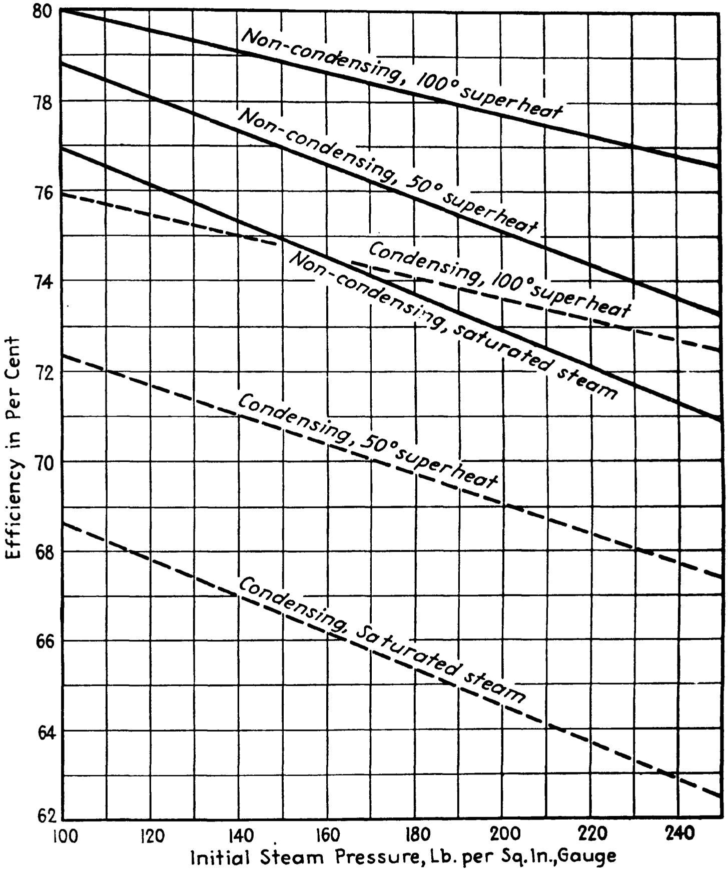
Pressure Lb./Sq. In., Gage	Max. temperature Deg. F.
150	800
200	800
250	850
300	850
400	900
600	900

FIG. I-1.—Theoretical steam rates for steam engines and turbines, operating noncondensing.

TABLE I-3.—APPROXIMATE EFFICIENCIES OF IMPULSE STEAM TURBINES AT FULL LOAD

(Based on data from Perry, "Chemical Engineers' Handbook," 2d ed., 1941, and Marks, "Mechanical Engineers' Handbook," 4th ed., 1941, McGraw-Hill Book Company, Inc., New York)

Horsepower	Efficiency	
	Noncondensing	Condensing
150	0.47	
300	0.48	
450	0.61	
600	0.63	
700	0.64	0.68
1,000	0.65	0.70
1,500	0.67	0.70
2,000	0.67	0.70
2,800	0.68	0.70



NOTE: Temperatures given are degrees Fahrenheit above saturation temperature.

FIG. I-2.—Approximate efficiencies, unaflow steam engines. (*Adapted from Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York, 1941.*)

c. Theory of the Ideal Steam Engine.—In the precise language of thermodynamics, the ideal engine expands steam by an adiabatic reversible process. Consequently,

$$S_2 = S_1$$
$$w = H_1 - H_2$$

where S_1 = entropy of steam, Btu/(lb) (°F)
S_2 = entropy of exhaust, Btu/(lb) (°F)
H_1, H_2 = heat content of steam, Btu/lb, at inlet, exhaust
w = work produced. Btu/lb

In other words, the entropy of the exhaust is precisely the same as that of the inlet steam, and the power developed is the mechanical equivalent of the heat abstracted from the steam. With this principle the theoretical steam rates for the ideal engine may be computed from the thermodynamic properties of steam. To compute the performance of a steam engine by use of a thermodynamic chart proceed as follows:

1. Find the point represented by the initial temperature and pressure of steam; read the heat content of steam, and record as h_1.

2. From this point follow the line of constant entropy until it crosses the pressure line corresponding to the exhaust pressure. Read the heat content and record as h_2.

3. The work produced is $h_2 - h_1$. This is in Btu per pound. The theoretical steam rate in pounds per horsepower-hour is $2544/(h_2 - h_1)$. The computation of the performance of an ideal steam engine from steam tables is illustrated by Example I-2.

Example I-2. Find the theoretical steam rate of an engine supplied with steam at 385 psig (400 psia) superheated to 600°F to be exhausted at 15.3 psig (30 psia). Finally compute the actual steam rate for an engine rated at 75 per cent efficiency.

SOLUTION:

1. Properties of inlet steam (400 psia, 600°F),

Heat content, $H_1 = 1306.9$ Btu/lb (Table E-15)
Entropy, $S_1 = 1.5894$ Btu/(lb)(°F)

2. Properties of steam saturated at 30 psia,

Heat content, $H = 1164.1$ Btu/lb (Table E-14)
Entropy, $S = 1.6993$ Btu/(lb)(°F)

3. Properties of water saturated at 30 psia,

Heat content, $h = 218.8$ Btu/lb
Entropy, $s = 0.3680$ Btu/(lb)(°F)

4. Quality of exhaust steam,

Let x = weight fraction of condensate in exhaust
$1 - x$ = weight fraction of live steam in exhaust (quality)
Entropy of exhaust steam $= S_2 = S_1 = 1.5894$ Btu/(lb)(°F)

$$S_2 = S_1 = xs + (1 - x)S$$

or

$$S - S_1 = (S - s)x$$

and

$$x = \frac{S - S_1}{S - s} = \frac{1.6993 - 1.5894}{1.6993 - 0.3680} = \frac{0.1099}{1.3313}$$

$$= 0.0824$$

$$1 - x = 0.9176$$

5. Heat content of exhaust steam,

$$\begin{aligned} H_2 &= (1 - x)H + xh \\ &= H - xH + xh \\ &= 1164.1 - 0.0824 \times 1164.1 + 0.0824 \times 218.8 \\ &= 1164.1 - 96.0 + 17.9 = 1086.0 \end{aligned}$$

6. Work produced per pound of steam,

$$H_1 - H_2 = 1306.9 - 1086.0 = 220.9 \text{ Btu/lb}$$

7. Theoretical steam rate,

$$\frac{2544}{220.9} = 11.5 \text{ lb steam/hp-hr developed}$$

8. Actual steam rate,

$$\frac{11.5}{0.75} = 15.4 \text{ lb steam/hp-hr}$$

d. Throttling Control.—The speed of a turbine or steam engine may be controlled by throttling the inlet steam to a lower pressure or by throttling the exhaust to a higher pressure. (In the case of the turbine the speed may also be controlled by the number of nozzles opened.) Whether this control is effected by a direct speed control or by the output of the driven equipment, the steam rate will be determined by the conditions prevailing at the engine inlet and exhaust rather than by the pressure in the supply and exhaust mains.

The relative effect of throttling the steam to a steam engine is illustrated by Example I-3.

Example I-3. A steam engine is supplied by a main carrying 200 psig saturated steam and exhausts to 15 psig. Find the steam rates per horsepower: (1) at line pressure and (2) if steam is throttled to 150 psig.

SOLUTION:

1. Steam at line pressure,

$$\begin{aligned} \text{Theoretical} &= 16.9 \text{ lb/hp (Fig. I-1)} \\ \text{Efficiency} &= 0.73 \text{ (Fig. I-2)} \\ \text{Actual rate} &= \frac{16.9}{0.73} = 23.2 \text{ lb/hp-hr} \end{aligned}$$

2. Properties of steam after throttling,

No work is performed and heat loss is negligible, hence, heat content of steam at reduced pressure will be unchanged. At 215 psia saturated steam has a heat content of 1199 Btu/lb (Table E-14), and a temperature of 388°F (by interpolation of Table E-15). Saturation temperature is 366°F.

3. Steam rate at throttled condition,

$$\begin{aligned} \text{Theoretical} &= 19.5 \text{ lb/hp-hr} \\ \text{Efficiency} &= 0.75 \\ \text{Actual rate} &= \frac{19.5}{0.75} = 26.0 \text{ lb/hp-hr} \end{aligned}$$

e. Quality of Exhaust Steam.—The quality of steam exhausting from a steam engine or turbine may be computed readily from the properties of the steam, the power developed, and the heat lost. This is illustrated by Example I-4.

Example I-4. Compute the quality of steam exhaust from the engine considered in Example I-2, assuming a heat loss of 12 Btu/hp-hr.

SOLUTION:

1. Heat content of inlet steam = 1306.9 Btu/lb
2. Work produced for 1 lb steam,

$$\frac{1}{15.4} \text{ hp-hr, or } \frac{2544}{15.4} = 165.1 \text{ Btu/lb (result, Example I-2)}$$

3. Heat loss $= \frac{12}{15.4} = 0.8$ Btu/lb
4. Heat content of exhaust steam,

$$1306.9 - 165.1 - 0.8 = 1141.0 \text{ Btu/lb}$$

5. Heat content steam, water at exhaust pressure of 30 psia,

$$\begin{aligned} \text{Steam} &= 1164.1 \text{ Btu/lb} \\ \text{Water} &= 218.8 \text{ Btu/lb} \end{aligned}$$

6. Quality,

Let x = weight fraction condensate in exhaust

$1 - x$ = weight fraction live steam in exhaust (quality)

$$\begin{aligned} 1141.0 &= 1164.1(1 - x) + 218.8x \\ -23.1 &= -945.3x \\ x &= \frac{23.1}{945.3} = 0.024 \\ \text{Quality} &= 1 - x = 0.976 \end{aligned}$$

3. Steam Balance

Steam is most efficiently used when all of the exhaust from turbines and engines is just sufficient to supply normal requirements for process steam. Once preliminary estimates of the power and steam requirements are available, a tentative steam balance is usually a valuable guide for rounding out process design to provide for a more efficient use of steam. Example I-5 illustrates such a preliminary steam balance.

Example I-5. Preliminary estimates on a new process place the average steam demand at 150,000 lb/hr and the average power requirement of steam and electric driven units at 8,000 hp. Assuming that the process steam is supplied at 35 psig, determine whether a steam balance is possible and make a tentative choice of boiler pressure and superheat.

SOLUTION:

1. Assumed average quality of exhaust = 97% live steam
2. Total steam to be generated,

$$\frac{150{,}000}{0.97} = 155{,}000 \text{ lb/hr}$$

3. Over-all steam rate of turbines and engines,

$$\frac{155{,}000}{8{,}000} = 19.4 \text{ lb/hp-hr}$$

4. Assumed over-all efficiency of power generation = 65%
5. Corresponding steam rate of ideal engine,

$$19.4 \times 0.65 = 12.6 \text{ lb/hp-hr}$$

6. Steam pressures and temperatures which will give this rate (from Fig. I-1),

Pressure, Psig	Steam Temp., °F
600	Saturated
400	660
300	780

CONCLUSION: 400 psig steam at 660°F appears most suitable for preliminary estimates.

4. Internal-combustion Engines

a. Gas Engines.—The approximate fuel consumption of gas engines is given in Table I-4. This table is for larger engines with pistons 10 in. in diameter or over. Smaller engines will require 5 to 15 per cent more fuel per horsepower. The engine jackets remove about 3500 to 4000 Btu/hp-hr. The jacket water should preferably be rather warm and should be fairly soft. Lubrication requirements depend on a variety of factors. About 1 gal for every 2,000 hp-hr should be ample allowance.[1]

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[1] "Gas Engineers' Handbook," McGraw-Hill Book Company, Inc., New York, 1934.

TABLE I-4.—FUEL CONSUMPTION BY GAS ENGINES
(Graf, "Gas Engineers' Handbook," McGraw-Hill Book Company, Inc., New York, 1934)

Load	Fuel consumption, Btu/bhp-hr	
	4-cycle engines	2-cycle engines
5/4	11,000	15,000
4/4	10,000	13,000
3/4	11,000	16,000
2/4	12,500	17,000
1/4	17,000	23,000

b. Diesel Engines.—Data on performance of diesel engines are given in Table I-5. The jacket cooling water removes 2000 to 3500 Btu/hp-hr. Discharge temperatures above 180°F are not recommended. The lubricating oil requirement is about the same as for gas engines.[1]

TABLE I-5.—MANUFACTURERS' FUEL GUARANTEES
(Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York, 1941)

Make	Type*	Cycle	Size	Fuel consumption, lb/hp-hr		
				Full load	3/4 load	1/2 load
National Supply Co.	V, S	4	70–420	0.40	0.41	0.44
De La Vergne	V, A	4	100–300	0.42	0.435	0.52
Fulton	V, M, A	4	50–100	0.50		
Bush-Sulzer	V, A	2	500	0.425	0.44	0.52
Bush-Sulzer	V, S	2	1,800–2,400	0.39	0.40	0.43
American Locomotive	V, S	2	1,800	0.40	0.41	0.44
Nordberg	V, S	2	1,800–2,250	0.39	0.41	0.43
Hamilton M.A.N.	V, S	2	2,250	0.39	0.40	0.43

* A = air injection; S = solid injection; V = vertical; M = marine.

c. Gasoline and Kerosene Engines.—Manufacturers' data quoted by Marks[2] range from 0.46 to 0.72 lb of fuel per horsepower-hour. In the absence of specific data, 0.6 and 0.7 lb of fuel per horsepower-hour may be assumed for gasoline and kerosene, respectively.

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[1] Statements in this paragraph are based on data given by Perry, *op. cit.*

[2] Marks, "Mechanical Engineers' Handbook," 4th ed., McGraw-Hill Book Company, Inc., New York, 1941.

d. Waste-heat Recovery.—About one-third of the heat of combustion of fuel leaves engines with the exhaust. It is sometimes possible to utilize this heat. Table I-1 given earlier in the chapter gives data on waste-heat boilers operating on diesel exhaust.

5. Electrical Power

a. Generators.—The mechanical power required to drive an electric generator is

$$\text{Hp} = \frac{\text{kw}}{0.746 \times \text{efficiency}}$$

Representative efficiencies are given in Table I-6. This table is based on three-phase alternating current. The efficiency of single-phase and

TABLE I-6.—PERFORMANCE DATA FOR ALTERNATORS, HORIZONTAL-COUPLED, OR BELTED-TYPE ENGINE-DRIVEN GENERATORS
(Westinghouse Electric Corporation)
80% power factor, three-phase, 60-cycle, 240 to 2,400 volts

Kva	Poles	Speed, rpm	Kw excitation	Efficiency, (%)			Approx. net wt, lb
				½ load	¾ load	4/4 load	
25	4	1,800	0.8	81.5	85.7	87 6	900
93.8	8	900	2.0	87.0	89.5	90.9	2,700
250	12	600	5.0	90.0	91.3	92.2	6,000
500	18	400	8.0	91.7	92.6	93.2	10,000
1,000	24	300	14.5	92.6	93.4	93.9	18,600
3,125	48	150	42.0	93.4	94.2	94.6	52,000

Turbo-driven direct-connected type

Kva	Poles	Speed, rpm	Kw excitation at 125 volts	Efficiency %, at 80 per cent power factor			Cu ft air per min
				½ load	¾ load	4/4 load	
625	2	3,600	12	92.4	94.0	94.6	2,200
1,250	2	3,600	15	92.9	94.5	95.2	3,500
2,500	2	3,600	19	94.4	95.7	96.3	5,000
4,375	2	3,600	26	95.1	96.2	96.8	10,500
9,375	2	3,600	45	95.1	96.2	96.8	17,000
12,500	2	3,600	60*	95.1	96.2	96.8	23,500
25,000	2	3,600	100*	95.2	96.4	97.0	25,000
37,500	2	3,600	120*	95.7	96.8	97.4	55,000

* Excitation for these ratings is usually at 250 volts.

d-c generators is not greatly different. Complete data are readily obtainable from the manufacturers.

b. Motors.—The electrical power consumption of a motor is

$$\text{Kw} = \frac{0.746 \times \text{hp}}{\text{efficiency}}$$

Average efficiencies are given in Table I-7. Efficiencies of most other types of motors are not greatly different. Variable-speed alternating motors, however, have relatively poor efficiencies, and their use should be avoided if other types of drive are available.

TABLE I-7.—AVERAGE EFFICIENCIES FOR VOLTAGES UP TO 550 IN THREE-PHASE MOTORS

Rating, hp	Induction motors			Unity power factor, synchronous motors		
	Full load	¾ load	½ load	Full load	¾ load	½ load
1–2	81	79	76			
3–5	85	84	82			
10–25	87.5	87	85			
25–50	89	88.5	86.5	90	88.5	85
75–100	91	90	88	92	91	88
150–200	92	91.5	89.5	93	92	89.5
Above 200	93.5	93	91	94.5	93.5	92

The above are averages for 1,200- and 1,800-rpm motors.

Low-speed motors: Efficiencies will be from 1 to 2 per cent lower; 2,200-volt motors, 100 hp and above, have approximately the same efficiency as low-voltage motors. On smaller sizes the 2,200-volt motors have efficiencies 1 to 2 per cent lower.

Slip-ring motors in the smaller sizes will have full-load efficiencies of 1 to 3 per cent lower.

c. Carrying Capacity of Copper Wire.—Loads are given in Table I-8.

TABLE I-8.—ALLOWABLE CARRYING CAPACITIES OF COPPER WIRE AND CABLE (Standards of the National Board of Fire Underwriters)

No. A.W.G.	Cir mils	Amp		Cir mils	Amp	
		Rubber insulation	Varnished cambric insulation		Rubber insulation	Varnished cambric insulation
18	1,624	3	4	250,000	250	300
16	2,583	6	8	300,000	275	330
14	4,107	15	18	350,000	300	360
12	6,530	20	25	400,000	325	390
10	10,380	25	30	450,000	362	435
8	16,510	35	40	500,000	400	480
6	26,250	50	60	600,000	450	540
4	41,740	70	85	700,000	500	600
2	66,370	90	110	800,000	550	660
1	83,690	100	120	1,000,000	650	780
0	105,500	125	150	1,250,000	750	900
00	133,100	150	180	1,500,000	850	1,020
000	167,800	175	210	1,750,000	950	1,140
0000	211,600	225	270	2,000,000	1,050	1,260

d. General Electrical Data.

Ohm's law:

$$I = \frac{E}{R}$$

where I = current, amp
E = applied voltage
R = resistance, ohms

Applies to d-c circuits of any type and to a-c flow in noninductive circuits (such as heaters)

Power in direct and single-phase circuits:

$$P = fEI$$

where P = power, watts
f = power factor of circuit
= 1, for d-c and for any noninductive circuits or for synchronous motors
E = applied voltage
I = current, amp

Power in balanced 3-wire, 3-phase circuits:

$$\begin{aligned} p &= fEI \\ &= \sqrt{3}fE_LI_L \\ &= 3fE_pI_p \end{aligned}$$

where p = power, watts
f = power factor
E = circuit voltage
I = circuit current, amp
E_L = line voltage between any two wires
I_L = current in any one wire, amp
E_p = phase voltage
= E_L for delta systems
= $\frac{E_L}{\sqrt{3}}$ for Y systems
I_p = phase current, amp
= $\frac{I_L}{\sqrt{3}}$ for delta systems
= I_L for Y systems

Heat developed by resistance loads:

$$Q = 3.413EI = 3.413I^2R = 3.413E^2R$$

where Q = heat developed, Btu/hr
E = voltage
I = current, amp
R = resistance, ohms

Power consumed by electrolytic cells:

$$P = \frac{12.16nE}{\theta_e}$$

where P = power, kwhr/lb mole cell reaction
n = unit charge for 1 lb mole cell reaction, *i.e.*, number of equivalents per mole
E = applied voltage
= thermodynamic electromotive force divided by voltage efficiency
θ_e = current efficiency

CHAPTER J

PUMPS

Handling of liquids is a routine matter for the chemical engineer. This chapter gives performance data on several types of pumps and roughly outlines their fields of usefulness. The principal source of pump data for specific uses is the manufacturers who are very generous in supplying bulletins. Below are listed several texts on pumping liquids.

Kristal and Annett, "Pumps," McGraw-Hill Book Company, Inc., New York, 1940.

Nickel, "Direct-acting Steam Pumps," McGraw-Hill Book Company, Inc., New York, 1915. (Out of print.)

"Material Handling Cyclopedia," Simmons-Boardman Co., New York, 1921.

"Pump Handbook," Worthington Pump and Machinery Corp., Harrison, N. J.

Church, "Centrifugal Pumps and Blowers," John Wiley & Sons, Inc., New York, 1944.

1. General Data

a. Power Required for Pumping.—The work required to lift a liquid follows directly from the basic definition of work: force × distance. The force is the mass of liquid and the distance is the height raised, *i.e.*, the liquid head.

$$\text{Work (ft-lb)} = \text{weight (lb)} \times \text{head (ft)}$$

This is the useful work done; a greater amount must be supplied because of inevitable inefficiency. The over-all efficiency of a pump is defined as the ratio of work done to work supplied or, in terms of power, the ratio of water horsepower (theoretical power) to the brake horsepower applied to the pump drive. Introducing the efficiency and expressing work as power units (work per unit of time), the working equations given below may readily be obtained:

$$\begin{aligned}\text{Bhp} &= \frac{\text{lb/min} \times \text{ft head}}{33{,}000 \times \text{efficiency}} \\ &= \frac{\text{gpm} \times \text{psi differential pressure}}{1{,}713 \times \text{efficiency}} \\ &= \frac{\text{Gpm} \times \text{ft head} \times \text{sp gr}}{3{,}957 \times \text{efficiency}}\end{aligned}$$

Pumping efficiencies depend on the type of pump as well as on operating conditions; consequently, efficiencies are given under the type of pump. In computing the power required for pumping, the head and capacity must be those at the pump. The head must include pressure losses in lines and equipment, height through which the liquid is raised, pressure loss on control throttling in addition to the difference in pressures between the receiving vessel and the pump suction. Strictly speaking, the velocity head should also be included, but fortunately it may be neglected in all but a few cases, such as pumps operating at very low heads. The liquid pumped must include any by-passed to suction for control purposes. Treatment of these factors is illustrated by Example J-1.

Example J-1. 100 gpm of alcohol is to be supplied to a solvent recovery tower operated at 100 psig. As the process requires very close control, a dual control is employed, the pump discharge is maintained at constant pressure by a back-pressure controller by-passing liquid to the suction, and the flow into the system is finally controlled by a flow controller. The alcohol comes from a storage tank 1 ft above grade at atmospheric pressure. The liquid enters the tower at 49 ft above grade. The line has been sized for a total pressure drop from tank to tower of 10 psi. Estimate the power required using a turbine pump.

SOLUTION:

1. Head in pounds per square inch, differential,
net pressure head supplied,

Tower pressure − tank pressure	100 psi
Liquid head = 49 − 1 = 48 ft alcohol,	
or $\frac{\text{Specific gravity (60/60)}}{2.31} \times \text{head} = \frac{0.79}{2.31} \times 48$	16
Line drop	10
Drop through control valve	5
Total	131 psi

or, in feet of alcohol

$$\frac{131 \times 2.31}{0.79} = 383$$

2. Capacity,

Delivered to tower	100 gpm
Assume 10 per cent this amount throttled back to suction	10
Total	110 gpm

3. Pump efficiency,

From Fig. J-18, 40%, (slightly above typical is justified because flow is in upper portion of the range)

4. Horsepower required,

$$\frac{\text{Gpm} \times \text{psi}}{1{,}713 \times \text{efficiency}} = \frac{110 \times 131}{1{,}730 \times 0.40} = 21 \text{ hp}$$

b. Suction Lifts.—A liquid cannot exist at pressure below its vapor pressure. Even if a liquid has no appreciable vapor pressure, it is unstable under tension. Consequently, the theoretical minimum *absolute* pressure at pump suction is the vapor pressure of the liquid. The maximum *suction lift* is then the *barometric pressure* less the *vapor pressure* when both of these pressures are expressed as *height of liquid.* This may be done by the relation:

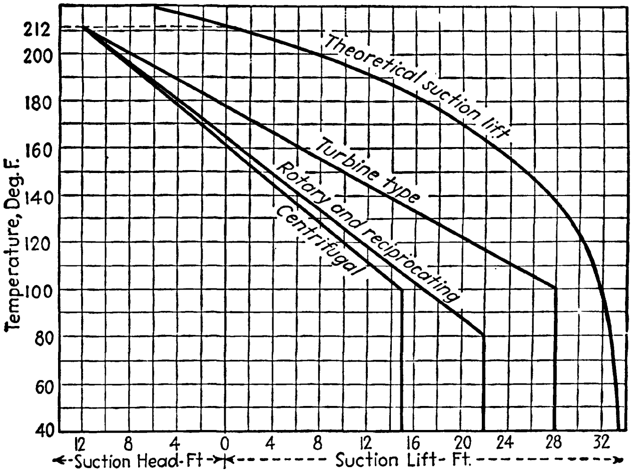

FIG. J-1.—Suction lifts for different types of pumps handling water. (*Kristal and Annett, "Pumps," McGraw-Hill Book Company, Inc., New York,* 1940.)

$$\text{Liquid head, ft} = \frac{2.31 \times \text{psi}}{\text{specific gravity } (60/60)}$$

The suction lifts *practical* for *actual* pumps are considerably below the theoretical value, and it is by far the best practice to operate pumps with a slight positive pressure (flooded suction), whenever possible. However, pumps properly primed will lift liquids to some extent.

Figure J-1 gives data on lifts practical for pumping water and Fig. J-2 for other liquids. These figures are based on a barometric pressure of 14.70 psi. At high altitudes barometric pressures are lower (see

Fig. C-1), and the lifts must be reduced accordingly. It will be noted from both of these figures that positive suction pressures are necessary for liquids of high vapor pressure. For boiler-feed pumps returning

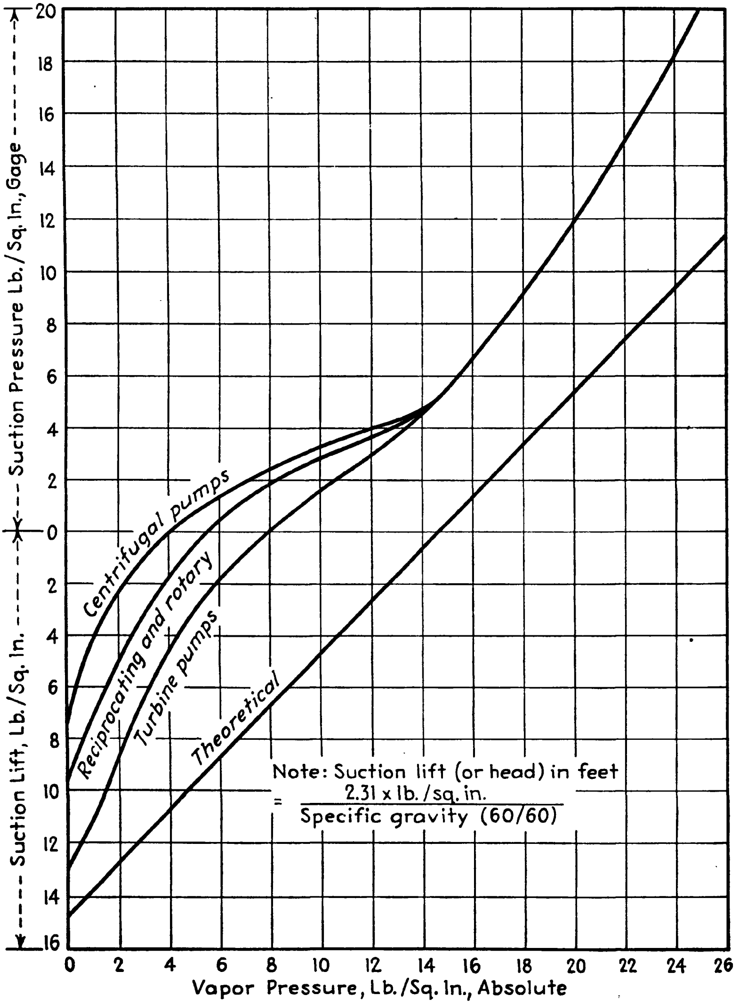

FIG. J-2.—Maximum suction lifts and minimum suction pressures for pumping volatile liquids.

condensate under pressure and at temperature above the atmospheric boiling point, the Standards of the Hydraulic Institute recommends a pressure at suction of 14 ft of liquid head above the vapor pressure including an allowance for variation of temperature of the condensate. This allowance amounts approximately to taking the vapor pressure about 10°F above the normal storage temperature. Presumably this same rule is applicable to other liquids; however, a greater allowance might well be desirable for liquids stored below the surrounding temperature (*e.g.*, liquefied natural gases).

The above discussion is intended to apply to the use of standard pumps. Actually, lower suction heads can frequently be used by careful selection of pumps in cooperation with the manufacturer.

c. Types of Pumps.—Although centrifugal and reciprocating pumps are the standard mainstays, other types have important applications. Reciprocating pumps are the oldest type and are extremely versatile since they handle almost any liquid and some slurries over any range of pressure and capacity. Their positive action favors control of rate by speed control. The type of motion is inconvenient for motor and turbine drives but is very advantageous for engine drives. In addition to the standard piston type, diaphragm pumps are available for handling corrosive and erosive materials.

Centrifugal pumps of volute and diffusion types are very popular. Although they cover a wide range of capacities, the smaller pumps are less efficient. Single-stage pumps afford only limited heads, but high pressures are easily obtained by multistage units. Rotary motion makes these pumps well suited to motor and turbine drives. The characteristics permit capacity control by either throttling or speed control, the former being a very attractive feature for electric-motor drives. Centrifugals are adaptable for pumping thick slurries.

Centrifugal pumps are classified further according to the shape of the impeller, which may be either single or double suction and may be designed to give a forward motion as well as outward, as in the Francis type, or still more in the axial or mixed flow type which is just one stage removed from the propeller pump. The propeller pump is well described by its name and is advantageous for high flows at low heads. These pumps supplement the "garden variety" of centrifugals, and the distinction between them is of secondary importance for purely process considerations.

Figure J-3 gives a rough idea of the relative economic choice between reciprocating and centrifugal pumps for boiler-water service.

Turbine pumps (herein distinguished from diffuser type centrifugals sometimes also called "turbine" pumps) are an important supplement to reciprocating and centrifugal pumps. Their most useful range is up to 150 gpm. They develop fairly high heads by a single stage and give efficiencies that compare favorably with low-capacity centrifugals. The turbine pump is well suited for high suction lifts.

Rotary slide-vane, gear, and screw pumps have many important applications, particularly for low flows at high heads or handling liquids of high viscosity.

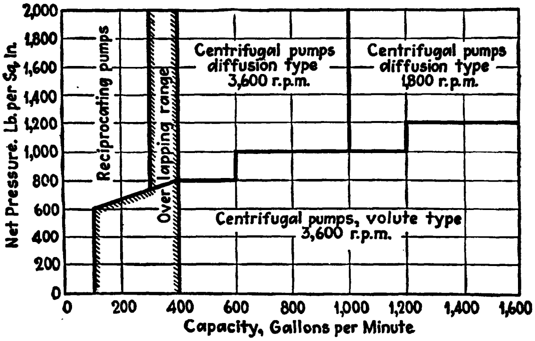

FIG. J-3.—Suggested economic operating range for reciprocating and centrifugal boiler-feed pump. (*Kristal and Annett, "Pumps," McGraw-Hill Book Company, Inc., New York,* 1940.)

2. Reciprocating Pumps

a. Capacity.—The capacity of reciprocating pumps is very nearly equal to the displacement. This is readily computed from the piston diameter, stroke, and pump speed. The calculated displacement multiplied by the volumetric efficiency is the capacity of the pump. Volumetric efficiencies of pumps are high (except for heavy viscous liquids) and may be taken as 97 per cent for most purposes since actual values are usually between 94 and 100 per cent. (In very large, efficient pumps, the efficiency may even exceed 100 per cent because of velocity effects.) Below are given formulas for pump capacity.

Single acting:

$$Q = \frac{E_v C N D^2 S}{295}$$

Doubling acting:

$$Q = \frac{E_v C N S (2D^2 - d^2)}{295}$$

where Q = gpm
E_v = volumetric efficiency
C = number of cylinders
N = strokes/min
S = length of stroke, in.
D = diameter of piston, in.
d = diameter of piston rod, in.

Table J-1 gives sizes and capacities of duplex steam pumps.

TABLE J-1.—SIZES AND CAPACITIES OF DUPLEX STEAM PUMPS (Courtesy of Worthington Pump and Machinery Corporation)

Size,* in.	Boiler feed capacity		Capacities for continuous service									
			Water and liquids under 250 SSU viscosity		Liquids 250–500 SSU viscosity		Liquids 500–1,000 SSU viscosity		Liquids 1,000–2,500 SSU viscosity		Liquids 2,500–5,000 SSU viscosity	
	Gpm	Boiler hp	Gpm	Piston speed, fpm	Gpm	Piston speed, fpm	Gpm	Piston speed, fpm	Gpm	Piston speed, fpm	Gpm	Piston speed, fpm
3 × 2 × 3	6	85	9.8	30	8.5	26	7.5	25	6	18	4.9	15
3½ × 2¼ × 4	8.5	120	14.5	35	12.5	30	11	27	8.5	21	7	17.5
4½ × 2¾ × 4	13	188	21.5	35	18.5	30	16.5	27	13	21	10.5	17.5
5¼ × 3½ × 5	24	348	40	40	35	35	31	31	24	24	20	20
6 × 4 × 6	35	505	59	45	51	39	45	35	35	27	29	22
7½ × 5 × 6	55	800	92	45	79	39	71	35	55	27	45	22
7½ × 4½ × 10	63	910	104	63	91	55	81	49	63	38	51	31
9 × 5¼ × 10	85	1,230	142	63	124	55	110	49	85	38	70	31
10 × 6 × 10	112	1,620	185	63	161	55	144	49	112	38	91	31
10 × 7 × 10	152	2,200	250	63	220	55	196	49	152	38	124	31

* Steam cylinder diameter × pump cylinder diameter × length of stroke.

b. Efficiencies.—Figure J-4 gives typical efficiencies of reciprocating pumps handling light liquids. Efficiencies handling viscous liquids will be lower, but unfortunately no specific data can be presented here in this regard, though Table J-1 gives the effect of viscosity on capacity and thereby gives an index of the order of effect to be expected.

c. Control.—Because of the high volumetric efficiencies, the capacity of a reciprocating pump is determined almost entirely on its speed; in fact, the speed of a pump in *good condition* is a fairly accurate measure of the flow. A pump driven by an electric motor will, therefore, deliver a constant flow nearly independent of head; moreover, the flow cannot be readily changed except by returning the excess capacity to the suction or by changing the length of the stroke. This latter expedient is employed in proportioning pumps. Control of flow by regulating the speed of the drive is an efficient method, as there is no loss of power from excess capacity or throttling. This fact accounts for the popularity of the steam pump as it largely offsets the low efficiency of the steam cylinder drive.

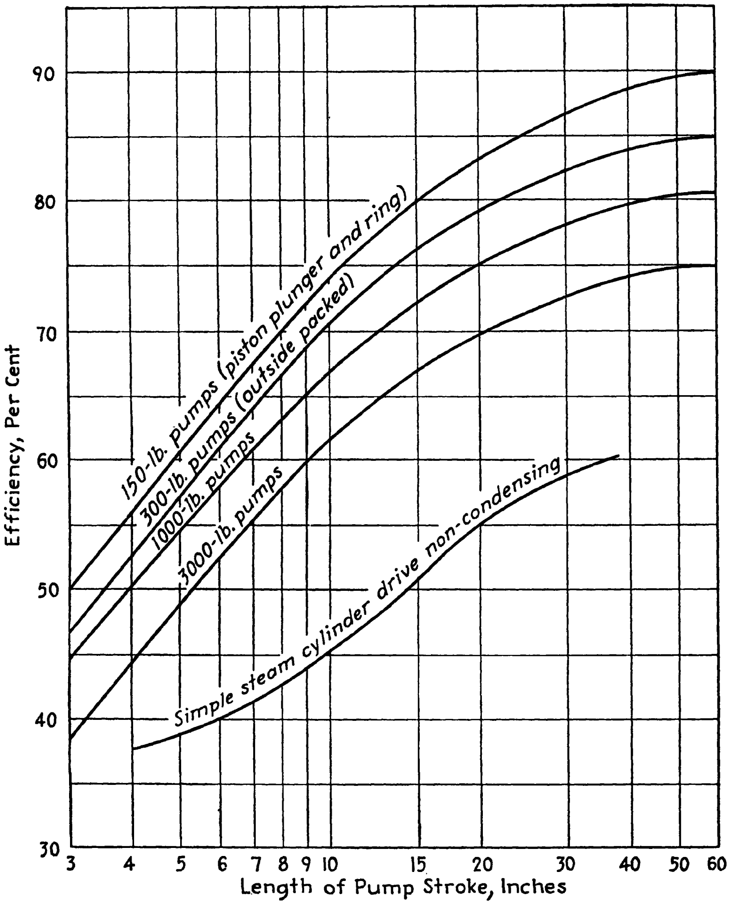

FIG. J-4.—Approximate efficiencies of direct-acting steam pumps. (*Adapted from Nickel, "Direct-acting Steam Pumps," McGraw-Hill Book Company, Inc., New York,* 1915.)

3. Centrifugal and Propeller Pumps

a. Performance Characteristics.—As already mentioned under pump types, centrifugals are made to give a wide range of characteristics by variation of impeller shape, speed, and number of stages. Illustrative performance data of single stage pumps are given as follows:

Characteristics of a centrifugal pump showing method for correction when speed is changed	Fig. J-5
Characteristics of pumps handling water compared with those handling viscous oils	Figs. J-6, J-7

Comparison of the characteristics of a centrifugal and a propeller pump .... Fig. J-8
Performance on handling paper stock .... Fig. J-9
Performance of a stoneware pump .... Fig. J-10

In addition to these performance curves, Fig. J-11 gives data on the approximate efficiencies of centrifugal pumps of different capacities; Fig. J-12 gives similar data showing the effect of the specific speed. This specific speed is an important criterion for pump design

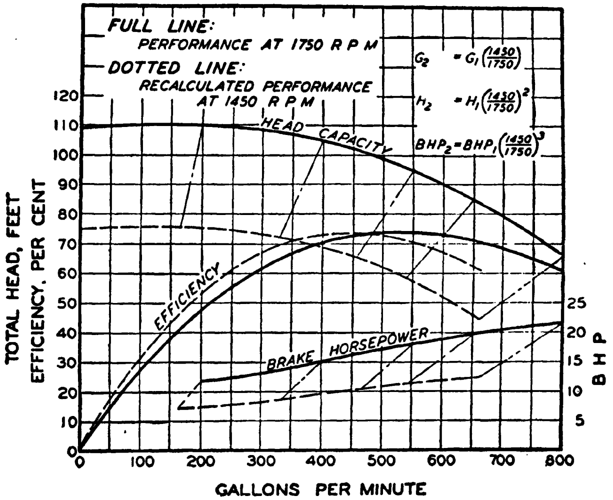

FIG. J-5.—Showing how characteristics at one speed may be converted into those at another. (*Graf, "Gas Engineers' Handbook," McGraw-Hill Book Company, Inc., New York,* 1934.)

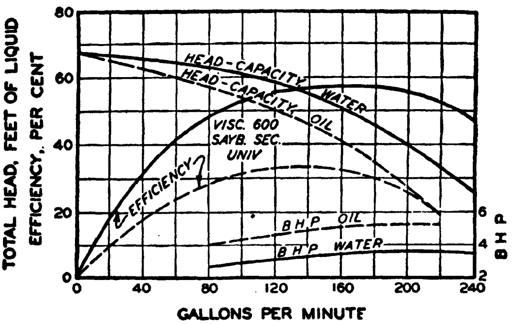

FIG. J-6.—Characteristics of 2-in. single-stage pump for water and 600 SSU oil. (*Graf, "Gas Engineers' Handbook," McGraw-Hill Book Company, Inc., New York,* 1934.)

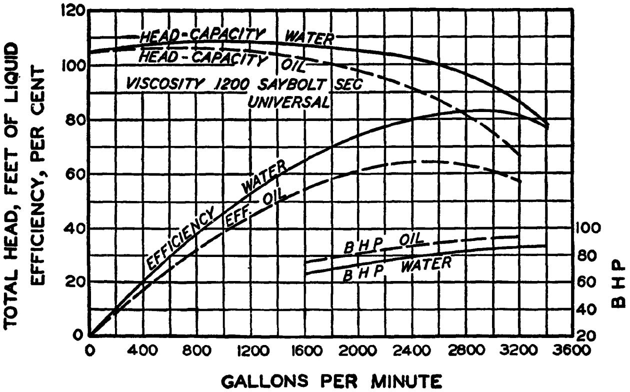

FIG. J-7—Characteristics of 10-in. double-suction pump for water and 1200 SSU oil. (*Graf, "Gas Engineers' Handbook," McGraw-Hill Book Company, Inc., New York,* 1934.)

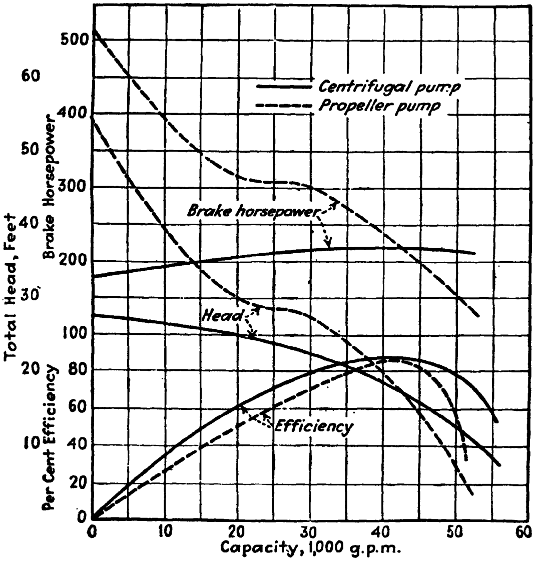

FIG. J-8.—Characteristic curves of a centrifugal- and a propeller-type pump, each rated 42,000 g.p.m. at 17-ft. head. (*Kristal and Annett, "Pumps," McGraw-Hill Book Company, Inc., New York,* 1940.)

and affords an index as to the number of stages and type of pump best suited for the intended service. The figure indicates the impeller type best suited. For specific speeds below the solid lines in the figure, it is advisable to divide the head into two or more stages so that the specific speed of each stage is in the efficient range; in fact, specific speeds below 800 are seldom recommended.[1] A possible exception is in the

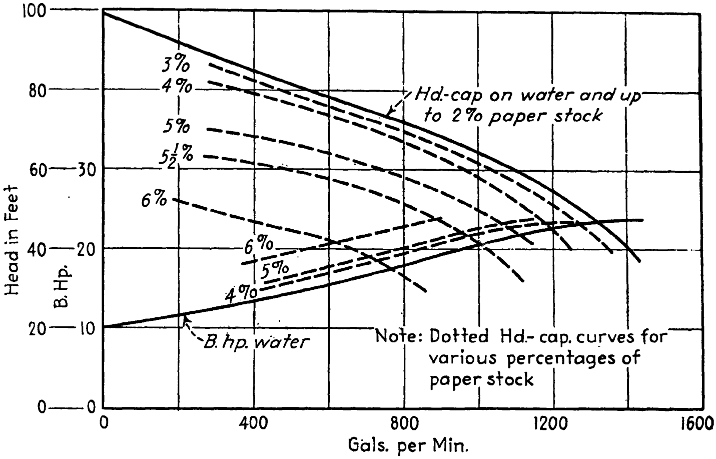

FIG. J-9.—Centrifugal-pump performance as affected by various consistencies of paper stock. (*By permission, Goulds Pumps, Incorporated.*)

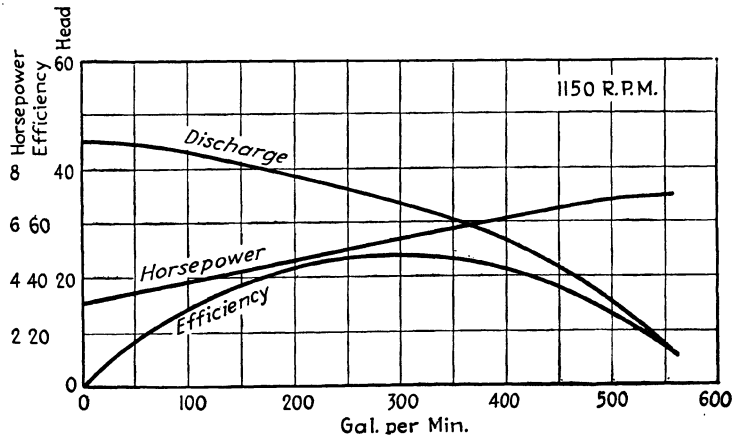

FIG. J-10.—Characteristics of a stoneware pump. (*By permission, General Ceramics and Steatite Corporation, Chemical Equipment Division, Keasbey, N. J.*)

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[1] Recently single-stage hot-oil pumps with high heads have become available. This presumably represents an advance in pump design for low specific speeds.

case of small pumps, as a very low efficiency may be preferred to the higher cost of multistaging.

The use of this figure is illustrated by example J-2.

Example J-2. It is desired to pump 150 gpm of water from a main at 35 psi to 220 psi. Find the number of stages required for a centrifugal pump operated at 3,600 rpm.

SOLUTION:

1. Head = 220 − 35 = 185 psi,

or

$$185 \times 2.31 = 428 \text{ ft of water head}$$

2. Specific speed, single stage,

$$N_s = \frac{\text{Rpm}\sqrt{\text{gpm}}}{H^{3/4}} = \frac{3{,}600\sqrt{150}}{(428)^{3/4}}$$
$$= 470$$

Efficiency from Fig. J-12 = 50 per cent.

3. Specific speed, 2-stage,

$$N_s = \frac{3{,}600\sqrt{150}}{(214)^{3/4}}$$
$$= 800$$

Efficiency from Fig. J-12 = 60 per cent.
Take 90 per cent of this for 2 stages = 54 per cent.

4. Specific speed, 3-stage,

$$N_s = \frac{3{,}600\sqrt{150}}{(143)^{3/4}}$$
$$= 1{,}100$$

Efficiency from Fig. J-12 = 63 per cent.
90 per cent of this = 57 per cent.

CONCLUSION: Three stages appear desirable even at this high speed. A single stage, though possible from the standpoint of specific speed, might lead to impractical peripheral speeds. This conclusion is strictly tentative since only one factor of the many entering into pump design has been considered; therefore, it should be used only for preliminary power estimates and tentative choice between centrifugal and other types of pumps.

Centrifugal pumps are widely used for handling thick liquids. Aisenstein[1] states that pumps of 3-in. or smaller suction generally handle liquids up to 800 SSU and that the larger pumps handle liquids

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[1] "Gas Engineers' Handbook," McGraw-Hill Book Company, Inc., New York, 1934.

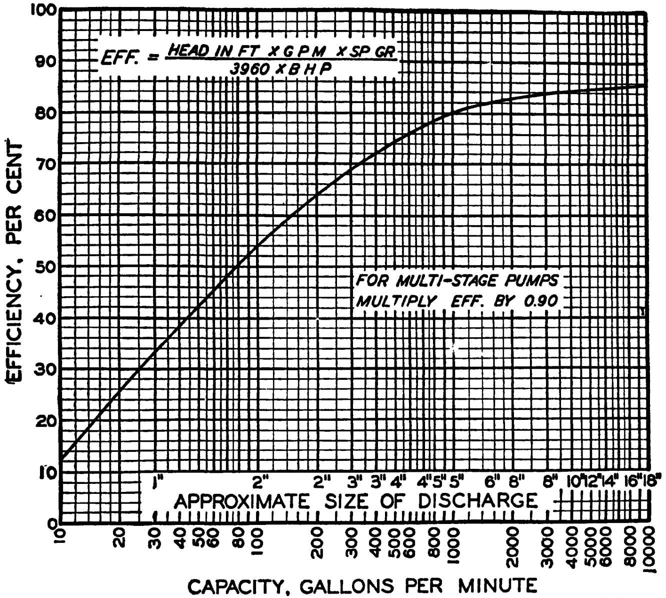

FIG. J-11.—Average efficiencies of double-suction pumps of various capacities (*Graf, "Gas Engineers' Handbook," McGraw-Hill Book Company, Inc., New York,* 1934.)

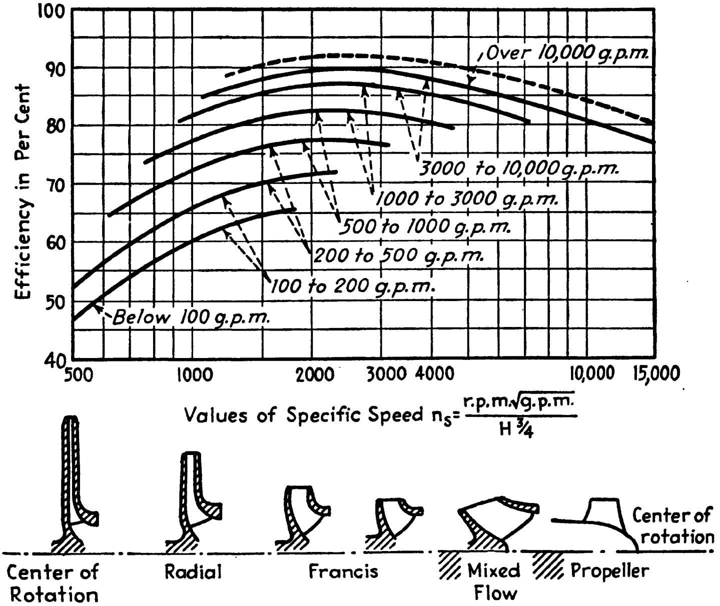

FIG. J-12.—Approximate relative impeller shapes and efficiencies as related to specific speed. (*Courtesy of Worthington Pump and Machinery Corporation.*)

up to 6000 SSU. Figures J-13 to J-15 permit a very approximate calculation of performance of centrifugal pumps handling viscous liquids. *It should be emphasized that these data may fail entirely as applied to some pumps. For example, pumps having water efficiencies of* 70 *per cent may have efficiencies anywhere from* 35 *to* 65 *per cent when handling liquids of* 200 *centistokes* (900 SSU). Inclusion of other factors, such as specific speed and liquid head, might lead to a more nearly adequate relation.

Explanation of Figs. J-13 to J-15 on Effect of Viscosity on Centrifugal Pump Characteristics[1]

Now we take correction factors for the 84 per cent efficient pump for capacity 0.94 and head 0.93 and 84 per cent efficiency will drop to 60 per cent, according to Fig. J-15. Note that Figs. J-13 and J-14 give correction factors for pump capacity and head, but Fig. J-15 gives on scale at left margin corrected efficiencies and not factors. The efficiency at the operating point will be lower in the ratio 81:84, or equals 57.8.

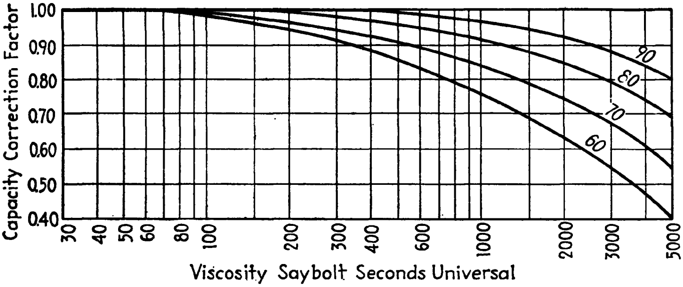

FIG. J-13.—Capacity-correction factor for pumps with water-peak efficiency as marked for capacity at best efficiency point. (*Courtesy of Oil and Gas Journal.*)

The operating point will come from 638 g.p.m. and 269 ft. head water performance as shown in Fig. J-16. Since the shutoff head stays essentially the same irrespective of viscosities, the head capacity curve for 1,000 seconds S.U.v. can be drawn through this point and the specified point using a suitable French curve.

Next calculate the brake horsepower for the specified head and capacity, using 57.8 per cent efficiency:

$$\text{Brake horsepower} = \frac{600 \times 250}{3{,}960 \times 0.578} = 65.5$$

Locate this point in Fig. J-16 and draw a brake-horsepower curve approximately parallel to the water brake horsepower. Now the efficiency for several capacities can be calculated from this brake-horsepower curve and the oil-head-capacity curve as shown in Fig. J-16.

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[1] Quoted from Stepanoff, *Oil Gas J.*, May 6, 1940, p. 78, (with changed figure numbering).

It should be understood that Figs. J-13, J-14, and J-15 are based on limited test data taken on pumps of many types and makes tested at different times by several investigators and therefore will not give results equally accurate

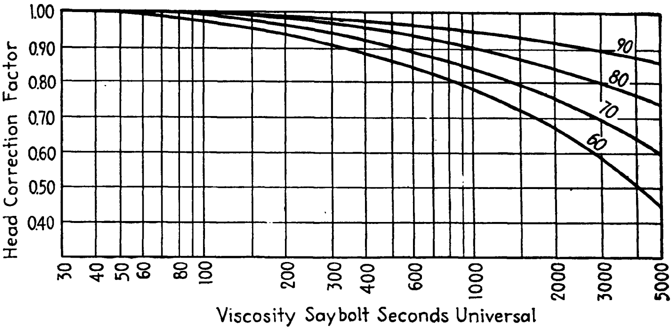


FIG. J-14.—Head-correction factor for pumps with water-peak efficiency as marked for head at best efficiency point. (*Courtesy of Oil and Gas Journal.*)

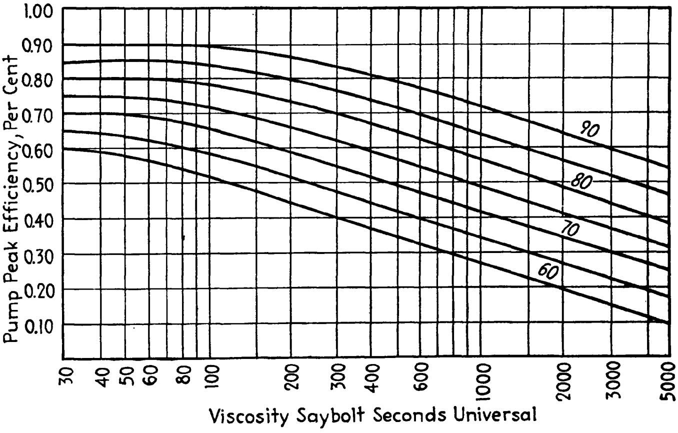


FIG. J-15.—Correction of centrifugal-pump peak efficiency obtained on water for pumping viscous petroleum oil. (*Courtesy of Oil and Gas Journal.*)

for all pumps. We believe, however, it is the best that can be done when taking into account the very complicated nature of pump behavior when handling viscous liquids. It is difficult to estimate the accuracy of these curves. . . .

In addition to the above described effects of the viscosity on the pump performance, pump behavior will be different when pumping oils if the pump operates at conditions approaching cavitation.

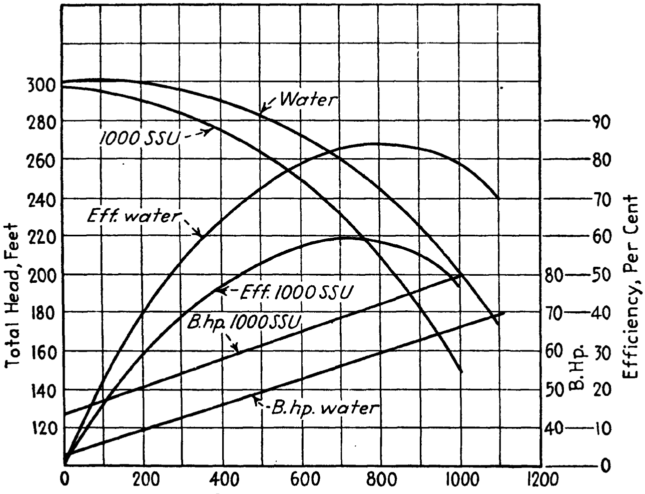


FIG. J-16.—Predicted characteristics for a 4-in. pump handling oil of 1000 Saybolt Universal viscosity. Computed from characteristics on water by factors given in figures J-13, J-14, and J-15. (*Courtesy of Oil and Gas Journal.*)

For slurries, clogging characteristics and plasticity must also be taken into account. Figure J-9 illustrates the behavior of pumps handling paper stock. The thickness of this material may be illustrated by the fact that a tumbler nearly full of 6 per cent paper stock must be tipped nearly 45 deg below horizontal before it drops out as a single "slug."

b. Control.—Centrifugal-pump delivery may be controlled by either speed regulation or by throttling. A steep characteristic (*i.e.*, a head that increases rapidly with decreased capacity as the pump in Fig. J-5) is best suited for speed control. A flat characteristic (nearly constant head) is best suited for throttling control.

4. Turbine Pumps

The term "turbine pump" is frequently applied to the diffuser-type centrifugal because of the mechanical similarity of that pump to a steam turbine. However, the term is intended here to refer to turbine pumps differing in type from centrifugals. These pumps, sometimes called "peripheral" or "regenerative" pumps, operate by the impulse principle.

The performance of a typical turbine pump is given in Fig. J-17. It will be noted that the peak of the efficiency curve is sharper than in the case of centrifugals, making the choice of pumps more sensitive. As in the case of centrifugal pumps, capacity may be governed by either speed or throttling. Since shutoff pressures are high, in some cases a relief valve may be needed.

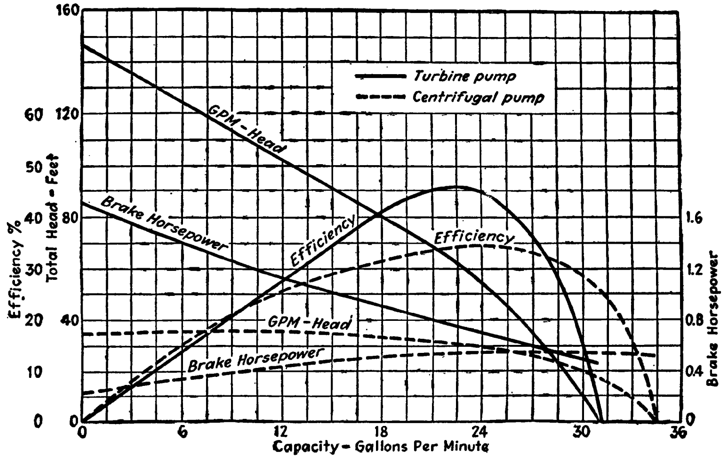


FIG. J-17.—Characteristic curves of centrifugal and turbine pumps. (*Kristal and Annett, "Pumps," McGraw-Hill Book Company, Inc., New York,* 1940.)

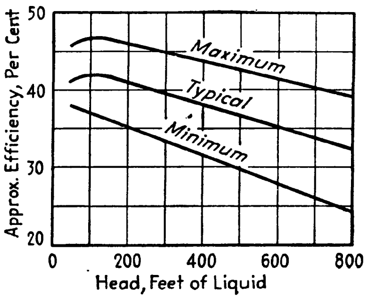


FIG. J-18.—Approximate range of efficiencies of turbine pumps, capacity 20 to 150 gpm.

Figure J-18 gives the approximate range of efficiencies of turbine pumps at different heads and requires explanation. The intent is not to give maximum efficiencies obtainable, but rather the probable efficiencies when standard pumps are employed for a particular service. Higher peak efficiencies are obtained, but operation at the peak would afford only a small allowance for overload.

5. Miscellaneous Types of Pumps

The performance of three pumps is presented as follows:

Rotary pump	Fig. J-19
Screw pump	Fig. J-20
Gear pump	Fig. J-21

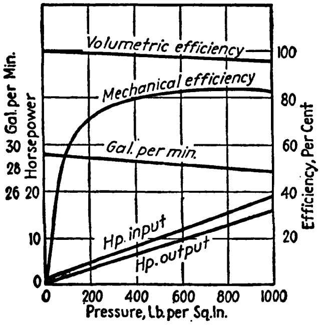


FIG. J-19.—Characteristic curves of a rotary slide-vane pump. (*Kristal and Annett, "Pumps," McGraw-Hill Book Company, Inc., New York, 1940.*)

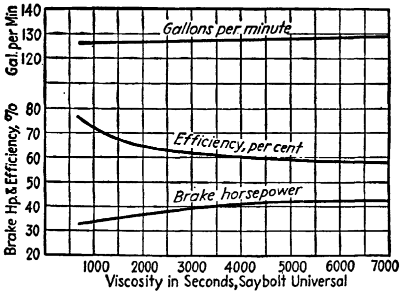


FIG. J-20.—Characteristic curves for a screw pump handling fuel oil. (*Kristal and Annett, "Pumps," McGraw-Hill Book Company, Inc., New York, 1940.*)

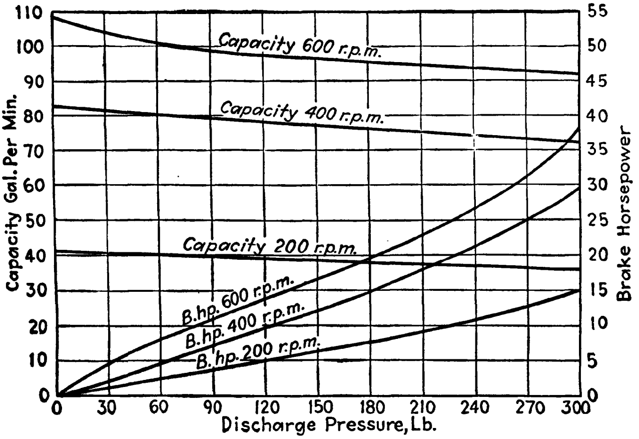


FIG. J-21.—Characteristic curves of spur-gear pump handling heavy oil. (*Kristal and Annett, "Pumps," McGraw-Hill Book Company, Inc., New York, 1940.*)

CHAPTER K

FANS, BLOWERS, AND COMPRESSORS

Wherever air or other gases are handled, fans, blowers, or compressors are encountered. Many excellent texts cover this equipment and, in addition, considerable information is given in texts on air conditioning and refrigeration. Manufacturers' bulletins and quotations are important sources of data and should not be overlooked. Below are listed a few of the many useful books.

Feller, "Air Compressors," McGraw-Hill Book Company, Inc., New York, 1944.
Gill, "Air and Gas Compression," John Wiley & Sons, Inc., New York, 1941.
Church, "Centrifugal Pumps and Blowers," John Wiley & Sons, Inc., New York, 1944.
Baumeister, "Fans," McGraw-Hill Book Company, Inc., New York, 1935.
Carrier, "Fan Engineering," Buffalo Forge Co., Buffalo, N. Y., 1935.
"Standard Methods Adopted for Centrifugal Fans and Blowers," National Association of Fan Manufacturers, Detroit, Mich., 1942.

1. Fans and Blowers

a. General Data.—Power required for moving gases may be computed in the same way as for pumping liquids. For last-place accuracy, a correction must be made for the compressibility of gas. In the case of fans and blowers this correction is small and may be neglected. This neglect will be justified later. The resulting equations follow:

$$\text{Bhp} = \frac{\text{cfm} \times \text{static head, in. of water (60°F)}}{6{,}356E_s}$$
$$= \frac{\text{cfm} \times \text{differential head, psi}}{229.3E_s}$$

where bhp = brake horsepower supplied
cfm = volume of gas including water vapor at suction temperature and pressure
E_s = static efficiency

In order to find the error introduced by neglecting the compressibility of the gas, we may compute the power required for compressing 1,000 cfm of air at 60°F and atmospheric pressure to 2 psig and compare the result with the value computed from the exact equation given under compressors. The results are 12.5 and 12.0 hp, respectively, Since these figures differ by only 4 per cent, it will be seen that use of the simpler formula is justified for most purposes up to 2 lb discharge. At the low pressures produced by most blowers the difference is entirely negligible.

When fans are used for circulating air against no measurable static head, the power required may be computed from the velocity. This power is the kinetic energy of the gas stream divided by the dynamic efficiency and may be conveniently computed by the equations below.

$$\begin{aligned}\text{Bhp} &= \frac{Qsu^2}{27{,}500{,}000E_d}\\ &= \frac{Wu^2}{126{,}000{,}000E_d}\end{aligned}$$

where bhp = brake horsepower of drive
Q = SCF/min (measured at 60°F, 30 in. Hg.)
s = specific gravity of gas; air = 1
W = lb/hr
u = velocity, fps
E_d = dynamic efficiency

Most blowers, even though designed to give static heads, discharge the gas at high velocity, and this velocity head is supplied by the blower. The velocity head may, for most purposes, be considered as a mechanical loss, and the power may be computed directly from the required static head and the static efficiency. If desired, the power may, however, be computed from the total dynamic plus static head and the total efficiency. This may be done either by adding the static plus dynamic power requirements or by first converting the dynamic head to static units and adding to the static head. In the latter case the power should be computed from the static formula and the total efficiency. The velocity head in static units is given by the expressions:

$$\text{Psi} = \frac{\rho u^2}{9{,}250}$$

$$\text{In. water} = \frac{\rho u^2}{326}$$

where ρ = gas density lb/cu ft, discharge conditions
u = gas velocity, fps

b. Performance Characteristics.—Figures K-1 and K-2 give performance characteristics of a propeller and centrifugal fan, respectively. Actually a wide variation of characteristics may be obtained for either type by employing different blade designs. Heads up to

60 in. of water may be obtained by fans, particularly if intended for operation under steady conditions. For heads above 20 in. of water, however, multistage units, *i.e.*, centrifugal and axial compressors, are frequently found desirable. Factors determining such choices are complicated and should be left to the specialist.

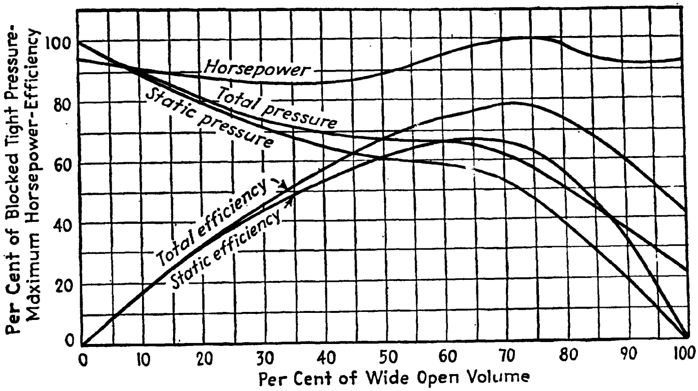


FIG. K-1.—Operating characteristics of axial airfoil type fans. (*Reprinted from p. 586 "Heating Ventilating Air Conditioning Guide,"* 1942.)

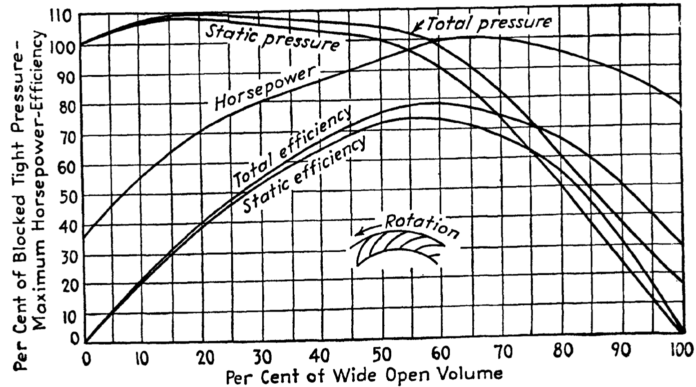


FIG. K-2.—Operating characteristics of centrifugal fans with blades curved backwards. (*Reprinted from p. 588 "Heating Ventilating Air Conditioning Guide,"* 1942.)

For general preliminary estimates the following efficiencies will usually be obtainable for steady services:

	Per Cent
Static efficiency	60
Dynamic efficiency when static head is 0	40
Over-all efficiency	70

2. General Data for Compressors

a. Power Requirement.—The work of compression of gases can be derived simply from the methods of thermodynamics as outlined in Chapter E. Gases are heated by compression unless the heat of compression is removed. In actual practice a portion, but not all, of this heat is removed. For the sake of definiteness, the calculation of the theoretical power is customarily based on either of two extreme assumptions: either that all of the heat is removed continuously during compression (isothermal), or that none at all is lost (adiabatic). For the isothermal case the work for compressing a perfect gas is [from Eq. (E-36)]

$$w = \int p\,dV = \int \frac{RT}{p}\,dp = RT \ln \frac{p_2}{p_1}$$

where w = work in the same units as RT
p = instantaneous pressure, any unit
p_1, p_2 = suction and discharge pressures
V = instantaneous volume
R = gas-law constant (see Table E-1)
T = absolute temperature, °R or °K, depending on units of R

Converting this equation to specific units of power and introducing the isothermal efficiency, we obtain

$$\text{Bhp} = \frac{MT}{3510E_I} \log \frac{p_2}{p_1}$$

where bhp = brake horsepower
M = SCF/min (measured at 60°F and 30 in. of Hg.)
T = suction temperature, °R
p_1, p_2 = absolute pressure at suction, discharge
E_I = isothermal efficiency
= ratio of ideal isothermal power to actual power

The second assumption of no heat loss, *i.e.*, of adiabatic compression, is much more universally used because the results are much closer to actual performance and also because the adiabatic efficiency afforded by a compressor is nearly independent of the properties of the gas being compressed. An additional assumption is also made in the case of perfect gases, namely, that the specific heat is constant. Under these circumstances the *adiabatic* equation of state of a perfect gas becomes

$$pv^{\gamma} = \text{a constant}$$

where p = instantaneous pressure

v = instantaneous volume

γ = adiabatic expansion coefficient

$= \frac{C_p}{C_v} = \frac{C_p}{C_p - R}$

C_p, C_v = specific heats at constant pressure, volume

R = gas-law constant, same units as C_p

The work of ideal adiabatic compression (also called "isentropic" compression) then becomes

$$w = \frac{RT}{n}\left[\left(\frac{p_2}{p_1}\right)^n - 1\right]$$

or

$$\text{Bhp} = \frac{T}{520}\frac{0.0643M}{nE}\left[\left(\frac{p_2}{p_1}\right)^n - 1\right] = \frac{p_1}{p_s}\frac{0.0643M'}{nE}\left[\left(\frac{p_2}{p_1}\right)^n - 1\right]$$

where w = work, same units as RT

R = gas constant

T = absolute temperature at suction, °R

p_1, p_2 = absolute pressures at suction, discharge

p_s = 14.73 psi, 30 in. Hg., etc.

$n = \frac{R}{C_p} = \frac{\gamma - 1}{\gamma}$

$\gamma = \frac{C_p}{C_v}$

C_p, C_v = specific heat at constant pressure, volume

M = SCF/min

M' = cu ft/min measured at suction conditions

E = adiabatic efficiency

Figure K-3 gives a graphical solution of this equation. The accuracy of this figure is about 1 per cent.

Actual gases do not fulfill either of the assumptions used in deriving the adiabatic power equation; the perfect gas law is not obeyed exactly, and specific heats are not constant but increase with both temperature and pressure. (Specific heats of monatomic gases at low pressure are independent of temperature.) Nevertheless the equation does, by good fortune, give reasonably accurate results for actual gases unless the gas-law deviation is very large. For example, the exact theoretical power requirement for two-stage compression of ethylene differs from the value determined by Fig. K-3 by only 2 per cent. It will also be noted by study of Fig. K-3 that the power of compression does not change much for small changes in specific heat or γ. On this account approximate values of either will suffice. Usually, good accuracy will be obtained by the use of the specific heat (or adiabatic compression exponent) at suction conditions. For gaseous mixtures the average specific heat may be used. Table K-1 gives approximate values of the expansion exponent. Data on specific heats are given in Chapter E.

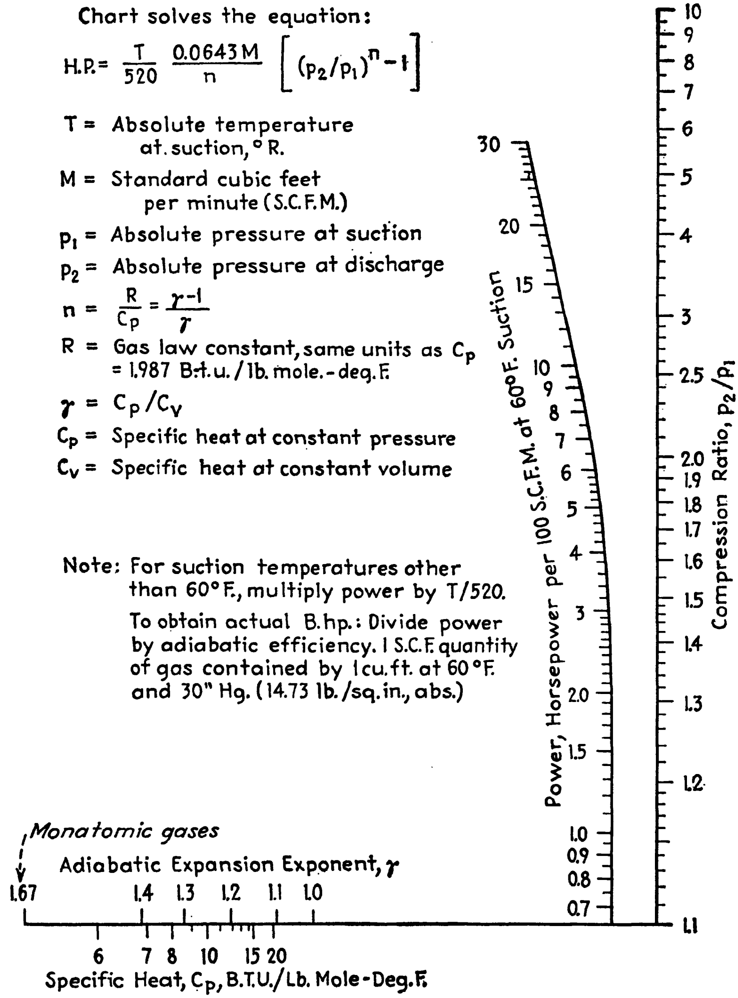


FIG. K-3.—Power required for ideal adiabatic compression of gases.

When imperfect gases are compressed, the use of thermodynamic charts such as Figs. E-20 and E-21 is recommended. The steps

TABLE K-1.—APPROXIMATE VALUES OF ADIABATIC EXPANSION EXPONENT OF COMMON GASES AT LOW PRESSURES AND 50 TO 100°F

Gases	Adiabatic Expansion Exponent, γ
Monatomic (He, Ne, Kr, Hg)	1.67
Most diatomic (O_2, N_2, Air, H_2, CO, NO)	1.4
Acetylene (C_2H_2)	1.28
Ammonia (NH_3)	1.31
Butanes (C_4H_{10})	1.1
Butylenes (C_4H_8)	1.1
Carbon dioxide (CO_2)	1.28
Chlorine (Cl_2)	1.33
Ethane (C_2H_6)	1.24
Ethylene (C_2H_4)	1.25
Hydrogen sulphide (H_2S)	1.33
Methane (CH_4)	1.31
Methyl chloride (CH_3Cl)	1.20
Propane (C_3H_8)	1.15
Propylene (C_3H_6)	1.16
Steam (H_2O)	1.32
Sulphur dioxide (SO_2)	1.27

involved in the use of these charts are outlined below (see Example E-1 in the chapter on thermodynamics):

1. Locate the point corresponding to inlet pressure and temperature—record enthalpy, H_1.
2. Follow the line of constant entropy to outlet pressure, record enthalpy, H_2, and temperature, t_2, (discharge temperature for ideal compression).
3. Work of compression $= H_2 - H_1$, or

$$\text{Hp} = \frac{(H_2 - H_1) \times \text{lb/hr}}{2{,}544}$$

where H_2, H_1 are in Btu/lb.

4. Repeat for each stage.
5. Divide by efficiency to secure brake horsepower.

b. Discharge Temperature of Compressed Gases.—For many purposes it is customary to take the ideal adiabatic temperature as close enough. This may be computed by the equation

$$T_2 = T_1 \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$$

where T_1, T_2 = absolute temperature at suction, discharge
p_1, p_2 = absolute pressure at suction, discharge
γ = adiabatic expansion exponent

However, it is equally easy to obtain a better value by a heat balance as follows:

$$t_2 = t_1 + \frac{2{,}544P - Q}{60MC_p} = t_1 + \frac{2{,}544P - Q}{Wc_p}$$

where t_1, t_2 = suction, discharge temperature, °F
P = brake horsepower
Q = total heat leaks, Btu/hr
= convection losses + heat removed by jacket water
M = SCF/min
W = lb/hr
C_p = specific heat, Btu/(SCF)(°F)
c_p = specific heat, Btu/(lb)(°F)

In the special case of single-stage reciprocating compressors using normal values of Q, this becomes

$$t_2 = t_1 + \frac{25P}{MC_p} = t_1 + \frac{1{,}500P}{Wc_p}$$

(Example E-1 illustrates the calculation of discharge temperature by use of thermodynamic charts.)

c. Water Vapor in Compressed Gas.—If gases contain water vapor, its volume must be included for computing the power. After compression and cooling, some of this water vapor becomes condensed, and the after- and intercoolers must remove the heat of condensation of the water vapor in addition to the heat of compression. The amount of vapor present may be computed from the vapor pressure of water and Dalton's law:

$$M_w = \frac{M_G p_w}{p - p_w}$$

where M_w = SCF of water vapor (1 lb = 21.02 SCF)
M_G = SCF of fixed gases
p = total pressure, absolute
p_w = vapor pressure water, same units as p (multiply p_w by $\frac{\text{relative humidity}}{100}$ for gases not saturated with water vapor)

The heat of condensation at room temperature is approximately 50 Btu/SCF.

d. Cooling Water.—The work of compression appears quantitatively in the heat content of the gas and must be removed if the conpressed gas is desired at the original temperature. This is 2544 Btu/hp-hr. The approximate cooling water requirement for a reciprocating compressor computed on this basis is given in Table K-2. Additional cooling will be required to condense any liquid products, such as water (see previous section), and may also be required because of the Joule-Thomson effect in the case of gases at very high pressures or gases near critical conditions. In this latter case, use of thermodynamic charts is desirable. This use is outlined below (see Example E-1 in the chapter on thermodynamics):

1. Find heat content of inlet gas = H_1, Btu/lb.
2. Add power input to obtain heat content of exit gas,

$$H_2 = H_1 + \frac{2{,}544 \text{ bhp}}{\text{lb}} \text{ Btu/lb}$$

(See Paragraph *a* for computing power.)

3. Find heat content of cooled compressed gas = H_3, Btu/lb.
4. Heat to be removed by aftercooler (or intercooler) = $H_2 - H_3$ Btu/lb.
5. Cooling water required,

$$\text{Gpm} = \frac{H_2 - H_3}{500 \times \text{temperature rise}}$$

Frequently the gas being compressed is a vapor and is entirely condensed in the aftercooler (condenser). In this case the use of thermodynamic charts, as just described, is identical except that H_3 equals the heat content of the condensed liquid. If thermodynamic charts are not available, the condensing load is simply the latent heat of vaporization. To this must be added about 20 per cent for cooling the compressed vapor to the saturation temperature.

TABLE K-2.—APPROXIMATE COOLING WATER REQUIREMENT FOR RECIPROCATING COMPRESSORS HANDLING FIXED GASES

	Btu/hp-hr	Gpm for each hp		
		10°F rise	20°F rise	40°F rise
Jackets	1000	0.20		
Inter-* and aftercoolers	1500	0.30	0.15	0.04
Total*	2500	0.50	0.25	0.065

* Additional is required to condense any liquid products; also, additional may be required if the Joule-Thomson effect is large.

e. Types of Compressors.—The standard method of compression is still the reciprocating compressor. These compressors are efficient and simple to design for all ranges of pressure and capacity. The reciprocating motion makes them particularly suited to engine drives. The chief disadvantages are relatively high maintenance and oil consumption.

The centrifugal and axial flow compressors are becoming increasingly popular for the larger capacities. As yet they are not common for the higher pressure ranges, though the only apparent limitation is customer demand. The efficiencies are in general only slightly below the reciprocating type, but frequently this is more than offset by lower costs of purchase and maintenance, together with the almost complete absence of oil spray in the compressed gas. Their rotary motion makes these compressors well suited for motor or turbine drive.

Rotary compressors of various types have important applications. At low heads their efficiencies compare favorably with reciprocating and are well suited to small capacities. The liquid piston type uses no lubrication other than the sealing liquid (usually water).

3. Reciprocating Compressors

a. Power Requirement for Single-stage Compressors.—The approximate efficiencies of reciprocating compressors are given in Fig. K-4. The values given are considered conservative. In fact,

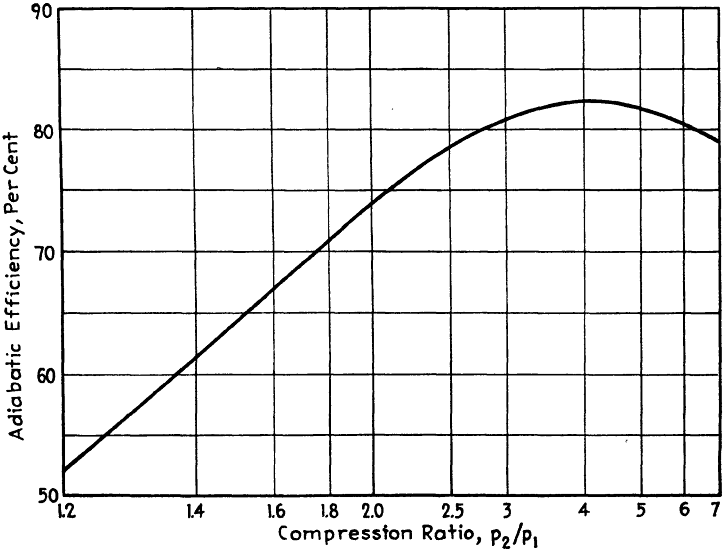
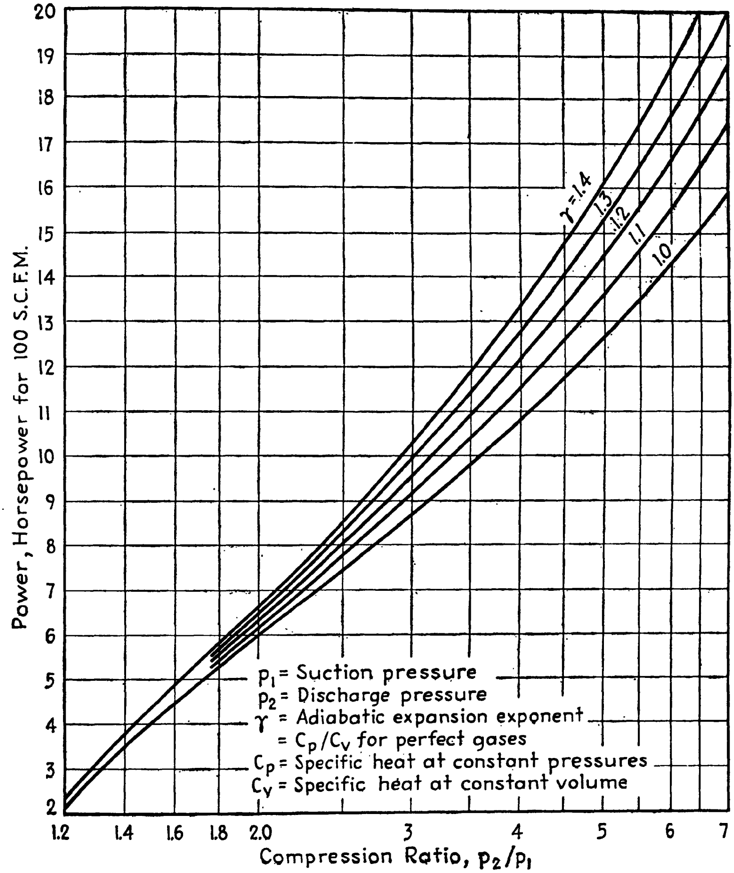


FIG. K-4.—Approximate efficiencies of reciprocating compressors. *(Based on data supplied by the courtesy of Clark Bros. Co., Inc.)*

considerably higher efficiencies are sometimes quoted; for example, Feller[1] states that "large steam-driven compressors, when in first class condition, show a mechanical efficiency, when fully loaded of approximately 90%. Smaller steam-driven machines may show lower results, 87 to 90%." However, reciprocating compressors could not be expected to give such high efficiencies without frequent overhaul, and Fig. K-4 is probably about as good as any manufacturer would care to quote for sustained operation with adequate maintenance.



NOTE: For suction temperatures other than 60°F., multiply power by $\frac{T}{520}$, where T = absolute temperature, °R.

FIG. K-5.—Brake horsepower for reciprocating compressors. (*Based on data supplied by the courtesy of Clark Bros. Co., Inc.*)

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[1] "Air Compressors," McGraw-Hill Book Company, Inc., New York, 1944.

Actually the efficiency probably depends to some extent on the gas being handled. For example, performance on hydrogen would probably be several per cent below that on air or methane.

For most gases the power may be computed directly from Fig. K-5. Where the deviation from the perfect gas law is excessive, use of thermodynamic charts and Fig. K-4 is recommended.

b. Power Requirement for Multistage Compressors.—For compressors developing high pressures it is usually necessary to divide the compression into two or more stages with intercooling between stages, in order to obtain a good mechanical performance and to secure lower power consumption. If a constant adiabatic efficiency is assumed, it can readily be shown that the larger the number of stages, the more the power is reduced. In actual practice, *too* many stages actually increase the power owing to the lower efficiencies obtained and the added power required to supply the pressure drop in the intercoolers. From the standpoint of lowest power, compression ratios of the individual stages should be, roughly, between 2.5 and 6. Because of higher temperatures developed at high compression ratios it is usually desirable to keep the compression ratio below 5 in order to keep the cylinder walls cool, or for other reasons such as avoiding decomposition of the gas handled or danger of oil ignition.

The power required for multistage compressors may be computed by treating each stage separately as a single-stage machine. For obvious mechanical reasons it is desirable to balance the stages so that each requires the same power. This condition is closely fulfilled when the compression ratios of all stages are identical, that is, (neglecting the pressure drop in the intercoolers between stages),

Two-stage,

$$\frac{p_1}{p_0} = \frac{p_2}{p_1} = \sqrt{\frac{p_2}{p_0}}$$

Three-stage,

$$\frac{p_1}{p_0} = \frac{p_2}{p_1} = \frac{p_3}{p_2} = \sqrt[3]{\frac{p_3}{p_0}}$$

Four-stage,

$$\frac{p_1}{p_0} = \frac{p_2}{p_1} = \frac{p_3}{p_2} = \frac{p_4}{p_3} = \sqrt[4]{\frac{p_4}{p_0}}$$

where p_0 = absolute pressure at suction

p_1, p_2, p_3, p_4 = absolute pressure at discharge stages 1, 2, 3, 4

With compression ratios as so calculated, the power for each compression stage may be readily computed, but the total will not include the extra power required because of the pressure drop through the intercoolers. This is most accurately done by estimating the actual pressure drops and adjusting the compression ratios. However, this refinement is seldom necessary, as increasing the power by 2 per cent is usually sufficient allowance, provided the compression ratios of individual stages are above 2.

c. Jacket Water.—The jacket water requirement of compressors depends on mechanical design. In general a high velocity is required so that only about 10°F temperature rise should be assumed for a single pass. If a higher temperature rise is desired, a circulating system should be employed with sufficient fresh water added to hold the desired temperature. Obviously very hard water should be avoided to prevent scale formation. Usually rather warm cooling water is preferred. Feller[1] recommends discharge water temperatures between 100 and 160°F. Approximately 1,000 Btu/hp-hr is removed by cooling water. Table K-2 given under general data gives a useful summary of typical rates for cooling water requirements of compressors handling fixed gases. Small compressors are frequently designed for air cooling by fins to obviate the use of cooling water. This expedient is not practiced in the larger sizes.

d. Lubrication.—The lubricating oil actually used by compressors depends largely on the care of supervision by the operator. One gallon per 1,000 hp-hr is a reasonable allowance for preliminary estimates. Nearly all the oil used will leave as spray in the compressed gas and must be removed if an oil-free product is desired.

Reciprocating compressors can be operated with water lubrication by use of leather crimps or carbon rings. In the latter case, lubrication may be eliminated entirely at the expense of increased maintenance. In general, where oil must be excluded, other types of compressors should be considered.

e. Capacity of Reciprocating Compressors.—The volume delivered is the piston displacement divided by the volumetric efficiency. Below are given formulas for capacity:

Single acting:

$$M = \frac{E_v C N D^2 S}{2,200}$$

Double acting, no tail rod:

$$M = \frac{E_v C N S(2D^2 - d^2)}{2,200}$$

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[1] Feller, *op. cit.*

where M = cfm measured at suction conditions
E_v = volumetric efficiency
C = number of cylinders
N = strokes/min
S = length of stroke, in.
D = diameter of piston, in.
d = diameter of piston rod, in.

The volumetric efficiency depends on a number of factors, of which the piston clearance and the compression ratio are the most important. The clearance is the ratio of minimum volume between piston and exit valves to the displacement. Gill[1] gives a nomograph for computing the volumetric efficiency from the clearance and the compression ratio. Unfortunately, the clearance is usually an unknown factor. However, the equation below based on normal clearance, etc., may be used for estimating volumetric efficiencies directly:

$$E_v = 0.90 - \frac{0.03p_2}{p_1}$$

where E_v = volumetric efficiency
p_1, p_2 = suction, discharge pressures, absolute units

It is perhaps well to point out that very small compressors or those on vacuum service may have somewhat lower volumetric efficiencies.

f. Control.—Since the capacity of compressors changes only about 5 to 15 per cent on doubling the pressure, it is evident that throttling of the discharge is an ineffective method of control. The capacity is changed by different suction pressures, but suction throttling is very seldom advantageous. Consequently, speed control is the best method of regulating output. Where the compressor is electric-driven, the excess capacity may be by-passed back to the suction or "unloading" devices may be employed. These devices usually involve either pockets to increase the clearance, or blocking part of the valves. Unloading changes the compressor capacity by steps, and close regulation for steady delivery at intermediate values must be effected by additional equipment.

4. Centrifugal and Axial Compressors

These machines are really just multistage centrifugal and propeller fans, respectively. The development and application of both machines have expanded rapidly in recent years. Figure K-6 gives performance data for a centrifugal compressor; Fig. K-7 gives performance data of a centrifugal compressor with diffuser vanes for regulation

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[1] "Air and Gas Compression," John Wiley & Sons, Inc., New York, 1941.

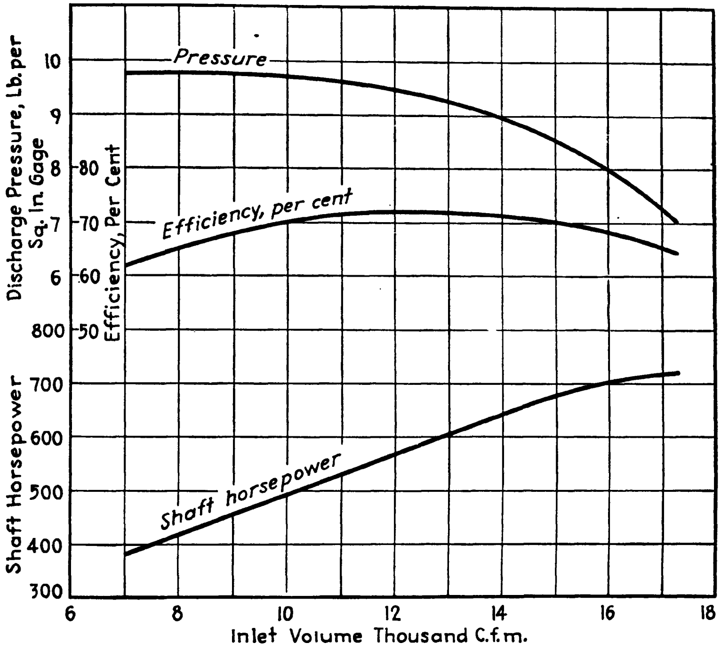

FIG. K-6.—Typical characteristic curve of a constant-speed machine. (*Courtesy of Roots-Connersville Blower Corp.*)

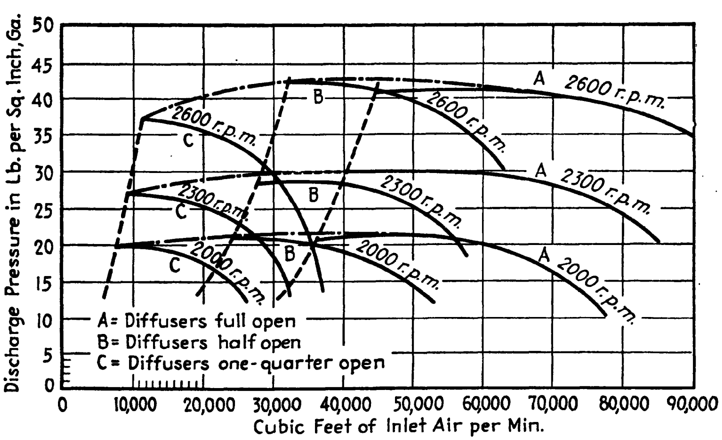

FIG. K-7.—Operating characteristics of a blower operating with movable diffuser vanes. (*Courtesy of Allis-Chalmers Manufacturing Company.*)

of capacity; Fig. K-8 compares the performance of an axial and centrifugal compressor. The centrifugal machines are quite flexible in their operation. They do exhibit critical speeds, but these are not usually troublesome except for flows very much below the full rating. In the smaller sizes critical speeds may be absent. In the case of axial compressors, critical speeds are an important consideration restricting operation to roughly, 80 to 120 per cent of the rated capacity. This requirement restricts application of these compressors to uses requiring fairly steady flows against fairly steady heads. Fortunately, however, these are a frequent process requirement so that there are many services in which axials can be used to advantage.

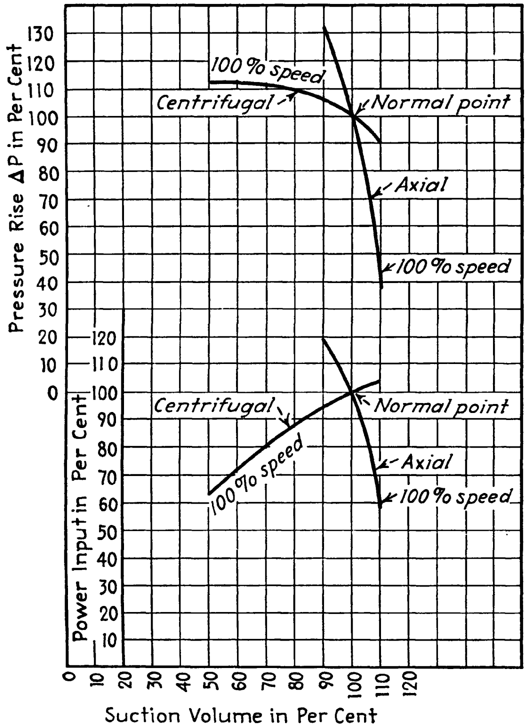

FIG. K-8.—Comparative characteristics of centrifugal and axial compressors at constant speed. (*Courtesy of Allis-Chalmers Manufacturing Company.*)

Typical efficiencies of centrifugal and axial compressors are given in Fig. K-9. These values are conservative. For example, Tucker[1] quotes 85 per cent adiabatic efficiencies for axial compressors and still higher values are believed obtainable. Efficiencies are relatively independent of gas density, temperature, and pressure. The number of stages required for high efficiency is, however, dependent on these factors.

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[1] *Chem. & Met. Eng.*, **51**, 96 (March, 1944), also personal communication; cf. Avery, *Allis-Chalmers Power Review*, August, 1939.

Water jackets are not required by these machines but are frequently included to improve the efficiency. For the higher pressure range, intercooling at one or more intermediate pressure is desirable to lower the power and improve the capacity. As in the case of reciprocating compressors, the power may be computed separately for each stage from suction to first cooler, and from there to second cooler, etc.

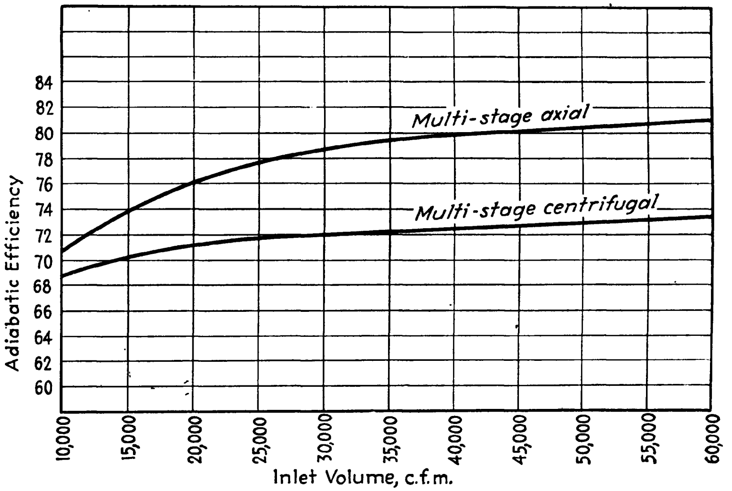

FIG. K-9.—Comparative efficiencies of centrifugal and axial compressors. (*Courtesy of Allis-Chalmers Manufacturing Company.*)

Centrifugal compressors are well suited for throttling control or control by diffuser vanes (see Fig. K-7). Speed control is also effective, particularly to obtain a constant flow against a variable head. Axial flow compressors are well suited for speed control when operating against a relatively constant head, but they are not well suited for throttling control.

The bearings of centrifugal and axial compressors are the only parts requiring lubrication. Consequently, the compressed gases will be substantially oil free.

5. Rotary Compressors

The A.S.M.E. test code classifies rotary compressors as ***sliding vane***, in which longitudinal vanes slide radially in a rotor mounted eccentrically in a cylinder; *two impeller*, in which two mating lobed impellers revolve within a cylinder; and *liquid piston*, in which a liquid serves to displace the air within a rotating element.[1]

Slide-vane compressors are reasonably priced but have disadvantages of high lubricating-oil consumption and comparatively high maintenance. Table K-3 gives data on single-stage compressors. Two-stage machines are made for pressures up to 125 psig and are not

TABLE K-3.—SINGLE-STAGE SLIDING-VANE COMPRESSOR CAPACITIES (Feller, "Air Compressors," McGraw-Hill Book Company, Inc., New York, 1944)

60-cycle, rpm	Lb gauge discharge pressure				Lb gauge discharge pressure			
	20	30	40	50	20	30	40	50
	Cfm, actual free air delivery				Hp rating of nearest commercial-size squirrel-cage motor			
1,160	32	31	.....	.....	5	5		
1,160	44	42	.....	.....	5	7½		
1,160	52	50	.....	.....	5	7½		
1,160	76	74	72	70	7½	10	15	15
1,160	83	82	80	78	7½	10	15	15
1,160	112	109	107	105	10	15	20	20
1,160	129	127	124	122	15	15	20	25
1,160	154	152	149	146	15	20	25	25
1,160	197	194	190	186	20	25	30	30
1,160	232	228	224	220	20	25	30	40
870	284	280	275	270	25	30	40	50
870	339	334	329	324	30	40	50	50
870	377	370	365	360	30	40	50	60
870	403	396	390	385	40	50	60	60
870	482	473	467	460	40	50	75	75
690	534	526	519	512	50	60	75	100
690	607	598	592	585	50	75	100	100
690	685	675	665	656	60	75	100	100
690	773	763	754	745	75	100	100	125
575	890	878	866	855	75	100	125	150
575	1,050	1,037	1,023	1,010	100	125	150	150
575	1,410	1,392	1,374	1,355	125	150	200	200
575	1,610	1,592	1,572	1,554	125	200	200	250

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[1] Feller, *op. cit.*

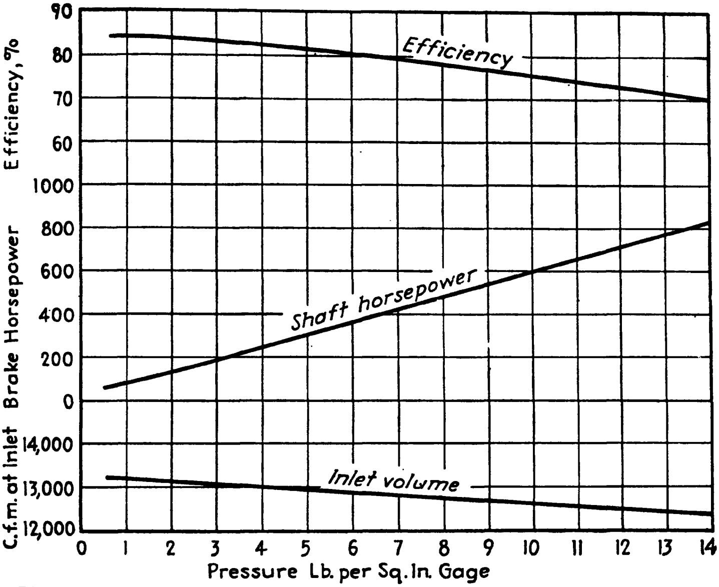

FIG. K-10.—Volume, horsepower, and efficiency curves of a 588 rpm, 12,500 cfm, 12-lb, two-impeller compressor. (*Courtesy of Roots-Connersville Blower Corp.*)

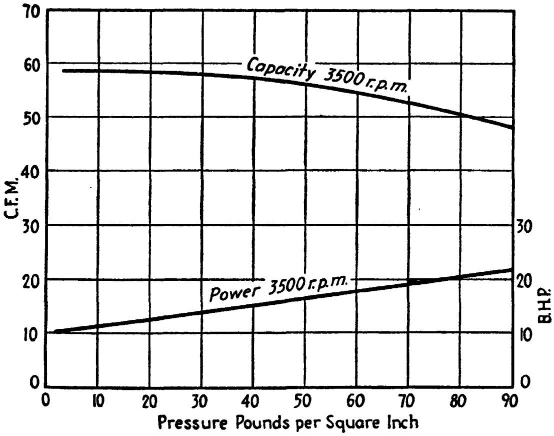

FIG. K-11.—Typical performance curve of a single-stage liquid piston compressor. (*Courtesy of Nash Engineering Company.*)

suited to throttling control. Water jackets are required for the larger sizes.

Two impeller compressors are advantageous for pressures between the most efficient ranges of blowers and reciprocating compressors. They are reasonably priced, but their oil consumption is appreciable and they are not suited to throttling control. Figure K-10 gives performance data on a large machine.

Liquid piston compressors present the advantages of using no lubrication and developing pressures up to 75 psig by a single stage. They are suited for either speed or throttling control. The performance of a small machine is given in Fig. K-11.

6. Vacuum Equipment

There is, of course, no magic in the atmospheric pressure of 14.6955 psi, the mean atmospheric pressure at sea level: and compressors of all types will work at pressures well below this (*i.e.*, in the vacuum range). The power requirement is computed in the same manner as the higher pressure equipment. The lower the absolute pressure, however, the larger the displacement required for the same weight of gas so that mechanical vacuum pumps run to size. Further, the volumetric efficiencies of all types of compressors are lower in the vacuum range and at very low pressures approach zero; that is, there is a definite limit to the vacuum any given machine can achieve. In general, rotary machines produce the best vacua, reciprocating next, and centrifugal machines the poorest.

By far the most popular device for industrial vacuum work is the

TABLE K-4.—AVERAGE STEAM CONSUMPTION STEAM JET EJECTORS
(Reprinted from "Cameron Hydraulic Data," 11th ed., 1942, by permission of the Ingersoll-Rand Company)
Pounds per hour at 100 psig pressure, steam pressure.

Weight mixture, lb/hr	% net dry air by weight	Suction pressure, in. Hg. abs									
		0.5		1.0		1.5	2.0	3.0	4.0		6.0
		3-stage	2-stage	3-stage	2-stage	2-stage	2-stage	2-stage	2-stage	1-stage	1-stage
10	100	73	99	59	70	58	50	42	38	58	36
10	70	59	84	47	60	49	42	35	31	63	39
10	40	45	68	33	47	38	32	26	23	68	41
10	10	24	45	16	28	21	17	14	12	74	42

NOTE: Steam consumption is directly proportional to capacity.

steam ejector. Steam ejectors are small, inexpensive, and have no moving parts. The steam consumption of these ejectors depends on a large number of factors which are listed below:

1. Absolute pressure of vacuum system.
2. Discharge pressure.
3. Steam pressure.
4. Cooling water temperature.
5. Density and quantity of fixed gases.
6. Quantity of water vapor.
7. Quantity, density, and saturation temperature of other vapors.

Table K-4 gives typical steam requirements for ejection of air and water vapor.

CHAPTER L

ABSORPTION, STRIPPING, DISTILLATION

The rectification processes of absorption, stripping, and distillation are closely related because they are methods for separating a mixture into its components by taking advantage of the difference in composition of gas and liquid in phase equilibrium. Fortunately, nearly all texts on chemical engineering present a good treatment of the basic theory. Several texts on these subjects are listed below.

Robinson and Gilliland, "The Elements of Fractional Distillation," 3d ed., McGraw-Hill Book Company, Inc., New York, 1939.

Hausbrand, "Principles and Practice of Industrial Distillation," John Wiley & Sons, Inc., New York, 1926.

Sherwood, "Absorption and Extraction," McGraw-Hill Book Company, Inc., New York, 1937.

Ruhemann, "The Separation of Gases," Oxford University Press, New York, 1940.

Design of rectification equipment involves the choice of the rectification cycle followed by separate consideration of the operations of absorption, stripping, distillation, compression, heat exchange, etc. Tentative process flows are adopted and the power, steam, cooling water, and equipment requirements computed. Several such computations should permit the choice of the preferred design flows.

The simplest measure of the difficulty of a rectification process is the theoretical plate. A perfect plate is defined as one in which the liquid leaving is in equilibrium with the vapor (or gas) leaving. The number of such plates required for the operation is dependent on the equilibria involved, the ratio of liquid to gas flows, the purity, and the recovery required. The actual number of plates required will in general be somewhat greater.

In case packed towers are to be used, the number of theoretical plates may still be used as the measure of rectification. The estimation of the height of an actual column equivalent to a theoretical plate (usually referred to as the H.E.T.P.) is not entirely straightforward; moreover, the theoretical treatment of this problem is beyond the scope of the book. Briefly, differential equations are set up for the local rate of diffusional transfer of key components between the liquid and the gas phases. The result may be expressed either in terms of the mass transfer coefficient or as the number of transfer units. This unit is defined mathematically and is similar to the theoretical plate except that it includes allowance for the difference between equilibrium and actual concentrations. In this way rules have been developed for computing the number of transfer units and also the required height for transfer unit (H.T.U.).

This section gives rules for computing the number of theoretical plates and transfer units from flows and equilibrium data, some useful equilibrium data, and data on sizing columns.

1. Absorption of Gases by Liquids

a. Kremser Method for Computing Theoretical Plates.—The performance of an absorption column may be computed from the following formula:[1]

$$E = \frac{Y_1 - Y_2}{Y_1 - Y_2^*} = 1 - \frac{A - 1}{A^{n+1} - 1} \qquad \text{(L-1)}$$

where E = absorption efficiency (see discussion)
Y_1, Y_2 = mole ratio gas being absorbed to inert gas in gas stream at inlet and outlet
Y_2^* = mole ratio in gas required for equilibrium with inlet liquid
A = absorption factor (see Table L-1)
n = number of theoretical plates

When $A = 1$, Eq. (L-1) reduces to

$$E = \frac{n}{n + 1} \qquad \text{or} \qquad n = \frac{E}{1 - E}$$

Figure L-1, based on this equation, may be used directly for computation of the number of theoretical plates. Table L-1 gives additional useful data.

No matter how high a column may be made, the best it can do is to establish equilibrium between the gas entering and the liquid leaving the base. This equilibrium represents the maximum amount of dissolved gas that can be carried out by a unit amount of liquid and, times the number of units circulated, represents the maximum quantity of gas that may be absorbed. This must be at least equal to the quantity of gas that is to be absorbed. Bare fulfillment of this condition represents the theoretical minimum circulation for complete absorption. *The ratio of liquid actually circulated to this theoretical minimum is the absorption factor.* The above statements are very generalized and may, perhaps, be clarified by repetition in terms of definite units (see Table L-1 for nomenclature):

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[1] Kremser, *Nat. Petroelum News*, **22**, No. 21, 42 (May 21, 1930); cf. Souders and Brown, *Ind. Eng. Chem.*, **24**, 519 (1932).

Maximum concentration dissolved gas at base of column $= x_2^* = \frac{y_1}{k}$

Quantity of gas to be absorbed $= G_1y_1$, moles/hr
Minimum condition for complete absorption,

$$L_1x_2^* = \frac{L_1y_1}{k} = G_1y_1 \qquad \text{or} \qquad L_1 = kG_1$$

Absorption factor for any liquid rate, $A = \frac{L}{kG}$

The absorption factor may, of course, be computed for any point in the column. If this factor is constant, then Fig. L-1 becomes nearly exact and is entirely so if only a small fraction of the inlet gas is absorbed. Actually, the absorption factor usually varies throughout the column. If the absorption factor is computed for both the top and the bottom, the actual absorption efficiency will usually be intermediate between the two corresponding values read off from Fig. L-1. Edmister[1] has proposed the following equation for an effective absorption factor:

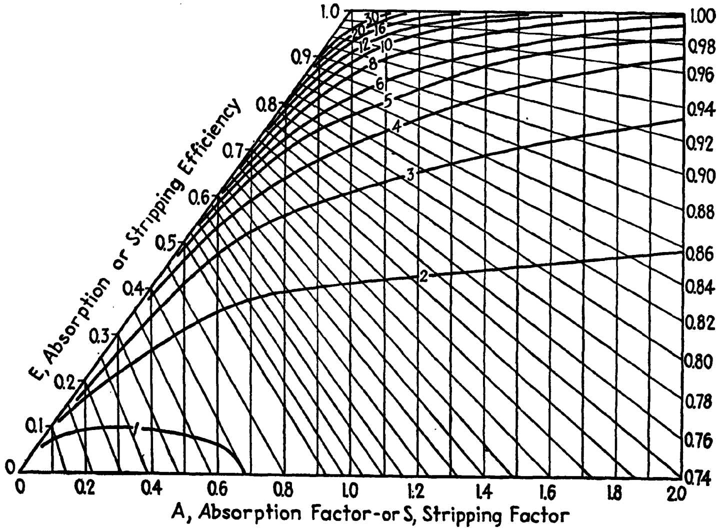

FIG. L-1.—Chart for computing the number of theoretical plates required for absorption or stripping operations.

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[1] *Ind. Eng. Chem.*, **35**, 837 (1943).

$$A_E = \sqrt{A_B(A_T + 1) + 0.25} - 0.50 \qquad \text{(L-2)}$$

where A_E = effective absorption factor for use in Eq. (L-1)
A_B = absorption factor at base of column
A_T = absorption factor at top of column

Table L-1.—Data for Computing Absorption Factors

Concentration in liquid	Concentration in gas	Equilibrium expression	Absorption factor	Stripping factor
x	y	Vaporization constant	$\frac{L}{kG}$	$\frac{kG}{L}$
x	y	Raoult's law	$\frac{pL}{p_vG}$	$\frac{p_vG}{pL}$
x	y	Henry's law	$\frac{pL}{HG}$	$\frac{HG}{pL}$
c	y	Bunsen coefficient	$\frac{p\beta L_v}{p_aG_v}$	$\frac{p_aG_v}{p\beta L_v}$
c	y	Ostwald coefficient	$\frac{p - p_s}{p_a - p} \frac{519\alpha}{T} \frac{L_v}{G_v}$	$\frac{p_a - p_s}{p - p_s} \frac{T}{519\alpha} \frac{G_v}{L_v}$

x = mole fraction (of component being absorbed or stripped) in liquid
x_1 = inlet; x_2 = base
x_2^* = mole fraction in liquid leaving if it is in equilibrium with inlet gas stream
c = concentration of dissolved gas, SCF gas/cu ft of solvent
y = mole fraction (of component being absorbed or stripped) in gas stream
y_1 = inlet gas; y_2 = exit gas; y_2^* = gas in equilibrium with inlet liquid
L = moles of total liquid per hour
L_v = cubic feet of dissolved gas free liquid per hour
G = moles of total gas per hour
G_v = SCF/hr, solvent vapor-free basis
p = system pressure (absolute)
p_v = vapor pressure of component to be absorbed
p_s = vapor pressure of solvent
p_a = standard atmospheric pressure (1 atm, 14.7 psi, etc.)
k = vaporization constant, the ratio of equilibrium concentrations: y/x
H = Henry's law constant, at equilibrium: $H = py/x$ (same units as p)
β = Bunsen coefficient expressed as SCF gas dissolved in 1 cu ft liquid when the partial pressure of gas is 1 atm. (As given in the "International Critical Tables," the gas volume is referred to 0°C and 1 atm. Multiply these by $\frac{520}{492} \times \frac{29.92}{30.0} = 1.05$ to convert to SCF/(cu ft)(atm)
α = Ostwald coefficient, volumes of pure gas dissolved in one volume of liquid when total pressure is 1 atm and volumes are measured at 1 atm and the temperature of interest
T = absolute temperature, °R

Use of the absorption factor computed in this manner increases the accuracy of estimating the number of theoretical plates by Eq. (L-1).

It is usually necessary to take the heat of absorption into account to secure the temperature at the base before accurately computing the absorption factor. If the heat capacity of the solvent is large compared to that of the gas, the gas will leave the column nearly at the temperature of the inlet liquid. The heat of solution then will all go to heating the liquid, and the temperature rise of the liquid times its heat capacity will equal the heat of solution. If the heat capacity of the gas is comparable with that of the liquid, it will absorb some of the heat also.

The absorption efficiency is the fraction of the soluble gas component that is absorbed by a solvent initially free from dissolved gas. In case the inlet liquid contains some dissolved gas, it can then at best reduce the exit gas only to the equilibrium concentration. One may compute this concentration from the equilibrium involved. From this the maximum possible fractional absorption of the gas may be computed. *This fraction times the absorption efficiency E, is the net fraction absorbed.* Repeating this in specific units (see Table L-1 for nomenclature),

Equilibrium concentration exit gas, kx_1

Minimum quantity of gas not absorbed, G_2kx_1

Quantity of gas in inlet stream, G_1y_1

Maximum possible fraction absorbed, $1 - \frac{G_2kx_1}{G_1y_1}$

Fraction actually absorbed, $E\left(1 - \frac{G_2kx_1}{G_1y_1}\right)$

The use of the methods outlined above is illustrated by Example L-1 which follows.

Example L-1. Make a preliminary process design for an absorber to be used (in conjunction with a stripper, and auxiliary equipment) for recovering a crude ethane from a by-product gas.

DATA:

1. Gas available, 250,000 SCF/hr
2. Gas composition,

H_2	70 mole %
CH_4	16 mole %
C_2H_6	12 mole %
C_3H_8	2 mole %

3. Absorption oil,
specific gravity 60/60°F = 0.825 (40° A.P.I.)

Approximate molecular weight, 200

4. Ethane recovery desired, 95%.
5. Cooling water available at 75°F.

TRIAL ASSUMPTIONS:

1. Operating pressure, 400 psia.
2. Inlet gas and oil temperatures, 85°F.
3. Exit temperature of oil, 90°F.
4. Dissolved gas in oil returned from stripper,

CH_4	0.00 mole %
C_2H_4	0.10 mole %
C_3H_8	0.20 mole %

5. Absorption of hydrogen is negligible.
6. Design for 10 theoretical plates based on base conditions.
7. Equilibrium constant data published by Brown ("Natural Gasoline Supply Men's Association Technical Manual," 4th ed., 1942. These data differ somewhat from data given in Fig. L-5 which was published after preparation of this example. Since this material is for illustration only, revision was not warranted.)

CALCULATIONS: Basis 1 hr.

1. Gas charged, $\frac{250,000}{379} = 660$ lb moles. Contains,

Hydrogen: $660 \times 0.70 = 462$ lb moles
Methane: $660 \times 0.16 = 105.6$ lb moles
Ethane: $660 \times 0.12 = 79.2$ lb moles
Propane: $660 \times 0.02 = 13.2$ lb moles

2. *Limiting* recovery for gas in equilibrium with oil,

Ethane: $k = \frac{y}{x} = 1.46$

$x = 0.001$ (inlet oil)

$y^* = kx = 0.00146$

Propane: $k = 0.47$

$x = 0.002$

$y^* = 0.002 \times 0.47 = 0.0009$

Methane: $k = 9.4$ but insufficient oil will be circulated for complete absorption.

Assume: $100 \times \frac{1.46}{9.4} \times 1.2 = 19\%$ absorption.

Residue gas (for equilibrium),

H_2: 462 lb moles
CH_4: $(1 - 0.19) \times 105.6 =$ 85.5
547.5

$$C_2H_6\text{:}\ \frac{0.00146}{1 - 0.00146 - 0.0009} \times 547.5 = 0.80 \text{ lb moles}$$

$$C_3H_8\text{:}\ \frac{0.0009}{1 - 0.00146 - 0.0009} \times 547.5 = 0.48 \text{ lb moles}$$

Fractional limiting recoveries,

$$C_2H_6\text{:}\ \frac{79.2 - 0.80}{79.2} = 0.990$$

$$C_3H_8\text{:}\ \frac{13.2 - 0.48}{13.2} = 0.964$$

3. Design based on conditions at gas inlet,

Absorption efficiency required for 95% absorption of ethane, $E = \frac{0.95}{0.99} = 0.96$.

From Fig. L-1, $E = 0.96$; $n = 10$; $A = 1.18 = \frac{L}{kG}$, or $L = 1.18\,kG$.

At assumed temperature of base = 90°F, $k = 1.51$.
Total liquid rate, $L = 1.18 \times 1.51 \times 660 = 1{,}178$ lb moles
Absorption factors for propane,

$$k = 0.50$$

$$A = \frac{1{,}178}{0.5 \times 660} = 3.55$$

E is nearly 1.
Fraction propane absorbed = $1 \times 0.964 = 0.964$.
Absorption factor for methane,

$$k = 9.5$$

$$A = \frac{1{,}178}{9.5 \times 660} = 0.188 = \text{fraction absorbed}$$

4. Quantities absorbed,

H_2 = none	
$CH_4 = 0.188 \times 105.6$	19.9 lb moles
$C_2H_6 = 0.95 \times 79.2$	75.2
$C_3H_8 = 0.964 \times 13.2$	12.7
Total	107.8 lb moles

5. Inlet oil = 1,178 − 108 = 1,070 lb moles,

$$1{,}070 \times 200 = 214{,}000 \text{ lb}$$

$$\frac{214{,}000}{0.825 \times 8.33} = 31{,}100 \text{ gal (520 gpm)}$$

$$\frac{31{,}100}{250} = 124 \text{ gal/1,000 SCF}$$

6. Temperature at base of column,
Heats of solution based on Table L-17.

CH_4 = small, neglect
C_2H_6 = 75.2 × 5,500 = 420,000 Btu (rounded values)
C_3H_8 = 12.7 × 6,500 = 80,000 Btu
Total.............. 500,000 Btu

Specific heat of oil from Table E-6 = 0.467 Btu/(lb)(°F).

$$\text{Temperature rise, } \frac{500{,}000}{0.467 \times 214{,}000} = 5°\text{F}$$

Temperature, 85 + 5 = 90°F. This checks the temperature used.

7. Design based on conditions at top of column,

Liquid charged = 1,070 lb moles.
Gas leaving = 660 − 98 = 562 lb moles

Equilibrium constant 85°F, 400 psig for C_2H_6, $k = 1.46$.
Absorption factor for ethane,

$$A = \frac{L}{kG} = \frac{1070}{1.46 \times 562} = 1.30$$

From Figure L-1, 10 trays: $E = 0.97$
This indicates that 10 theoretical plates would actually give somewhat better than the absorption efficiency of 0.96 required.

8. Corrected number of theoretical plates,

$$A_E = \sqrt{A_B(A_T + 1) + 0.25} - 0.50 \qquad \text{[Eq. (L-2)]}$$
$$= \sqrt{1.18 \times 2.30 + 0.25} - 0.50 = 1.23$$

For absorption efficiency = 0.96 and $A_E = 1.23$, eight theoretical plates are indicated by Fig. L-1.

DISCUSSION: These calculations show that a circulation of 520 gpm of lean oil and eight theoretical plates comprise a satisfactory process design. Calculations for more or less theoretical plates and different pressures are required before the best process design could be stated. Such factors are, however, seldom very critical; that is, small changes do not affect costs greatly. For preliminary considerations, less detailed calculations may be employed. The best short cuts vary with circumstances and cannot be recommended in advance. The reader can readily see that many of the corrections made could have been omitted without undue loss of accuracy. Trial assumption 4 would constitute the basis for stripper design.

b. McCabe-Thiele Method[1] for Estimating Theoretical Plates.—This graphical method is exact for the absorption of a single component. To apply this method, the concentrations are usually expressed as mole ratios, *i.e.*, moles of component being absorbed to moles of inert gases, and moles dissolved per mole of pure solvent. Weight ratios may also be employed, but percentages cannot be used directly. Two lines are plotted on plain coordinate paper. The *equilibrium line* is merely a plot of the equilibrium concentration in the gas phase plotted against the concentration in the liquid phase at the temperatures prevailing in the column. (If the heat of solution is appreciable, the temperatures must be obtained by heat balances.)

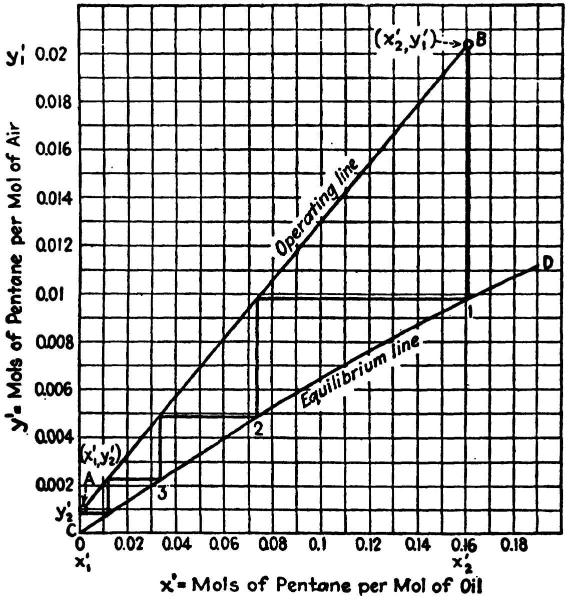

FIG. L-2.—McCabe-Thiele chart for absorption of pentane by oil. (*Nelson, "Petroleum Refinery Engineering," 2d ed., McGraw-Hill Book Company, Inc., New York,* 1941.)

The *operating line* is a straight line connecting the two points representing the actual operating conditions at the top and the bottom of the column, respectively. The *top* point is the concentration of liquid entering plotted against the concentration of the gas leaving. The *bottom* point is the concentration of liquid leaving the base against the gas entering.

The condition that the proposed operation may be performed, is that the operating line be everywhere *above* the equilibrium line (gas concentration plotted upward; liquid, across paper). If this condition is fulfilled, the number of theoretical plates may be stepped off by drawing alternate vertical and horizontal lines between the operating and the equilibrium lines. The number of steps is the number of theoretical plates required. The method is illustrated by Fig. L-2.

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[1] McCabe-Thiele, *Ind. Eng. Chem.*, **17**, 605 (1925).

In applying the McCabe-Thiele method, it is frequently found that the steps become very small at one end of the figure. This difficulty may be handled by constructing an enlarged chart of the troublesome end and treating it separately.

c. Calculation of Transfer Units.--The paper of Colburn[1] gives an equation for computing transfer units. His method involves the computation of "the slope of the equilibrium line," dy/dx. If this is constant, it becomes the vaporization constant and his equation may be reduced to

$$n_T = \frac{A}{A - 1} 2.3 \log \frac{A - E}{A - AE} \qquad \text{(L-3)}$$

where n_T = number of transfer units required (based on gas)
A = absorption factor (see Table L-1)
E = absorption efficiency

When $A = 1$, this equation reduces to

$$n_T = \frac{E}{1 - E} \qquad \text{or} \qquad E = \frac{n_T}{1 + n_T} \qquad \text{(L-4)}$$

This equation is valid when A is the same throughout the column. It will be noted that when $A = 1$, the number of theoretical plates and the number of transfer units are identical. For most conditions of industrial importance the number of transfer units is not greatly different from the number of theoretical plates required. For large values of A this is not true.

d. Other Methods for Computing Theoretical Plates.—A number of methods are described in the standard texts. The only procedure that is universally applicable with high accuracy is plate-by-plate iteration. The gas and liquid leaving each plate are assumed to be at equilibrium. The quantities leaving are obtained from a material balance and the plate temperature by a heat balance. Because this must be done at each plate, the computations frequently become tedious. Reference to standard texts should be made for details of these methods.

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[1] *Ind. Eng. Chem.*, **33**, 459 (1941).

2. Stripping Gases or Vapors from Liquids

a. Stripping with Inert Gas or Vapor.—In a stripper the gas or vapor stream flowing upward through the column picks up dissolved gases or volatile components. Thus it will be seen that the roles of gas and liquid are exactly reversed from the corresponding roles in an absorber. It should be expected, then, that the same laws should govern the two processes, provided the laws are restated in accordance with this reversal. Thus Eq. (L-1) becomes

$$E = \frac{X_1 - X_2}{X_1 - X_2^*} = 1 - \frac{S - 1}{S^{n+1} - 1} \qquad \text{(L-5)}$$

where E = stripping efficiency
X_1 = moles dissolved gas per mole of pure solvent in inlet liquid stream
X_2 = same mole ratio in outlet liquid
X_2^* = mole ratio required for equilibrium with inlet gas stream
S = stripping factor (the reciprocal of the absorption factor) (see Table L-1)
n = number of theoretical plates

Similarly, Eq. (L-3) becomes

$$n_T = \frac{S}{S - 1} 2.3 \log \frac{S - E}{S - SE} \qquad \text{(L-6)}$$

where n_T = number of transfer units required
S = stripping factor (see Table L-1)
E = absorption efficiency

The Edmister equation for correction of the stripping factor is

$$S_E = \sqrt{S_T(S_B + 1) + 0.25} - 0.50 \qquad \text{(L-7)}$$

where S_E = effective stripping factor for use in Eq. (L-5)
S_T = stripping factor at top of column
S_B = stripping factor at base of column

The McCabe-Thiele method is applied in exactly the same manner as for absorption. The condition that the operation is a possible one is, however, just reversed: the operating line must be everywhere *below* the equilibrium line. This method is illustrated by Fig. L-3.

b. Other Factors.—The stripper is usually operated at a higher temperature than the absorber, and frequently at a different pressure. A certain amount of dissolved gas contained in the solvent from the stripper may well be displaced by the increased temperature or from reduced pressure. Any dissolved gas so "flashed" off is already stripped and should not be included in the liquid feed. In this case, the simplest procedure is to assume that the liquid charged is at equilibrium with gases flashed off and to compute its composition on this basis. (Actually the liquid may contain a greater amount of dissolved gas, *i.e.*, be supersaturated, but an additional allowance of one theoretical plate is ordinarily ample to cover this lack of equilibrium.)

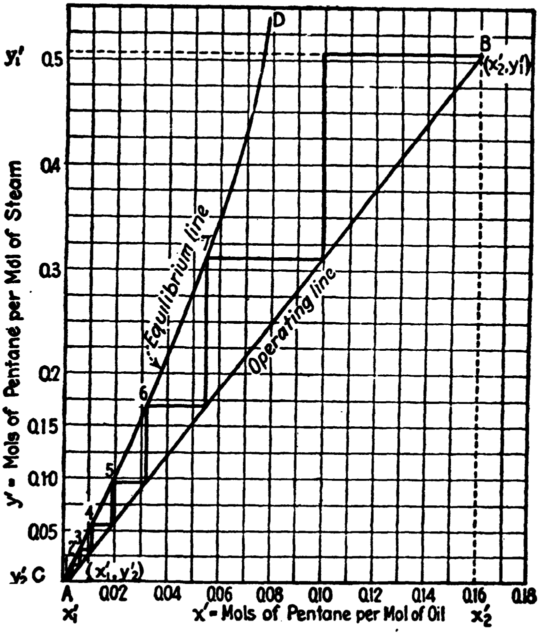

FIG. L-3.—McCabe-Thiele diagram for stripping pentane from oil. (*Nelson, "Petroleum Refinery Engineering," 2d ed., McGraw-Hill Book Company, Inc., New York,* 1941.)

Because of the higher temperatures of stripper operation, the solvent vapor pressure may be appreciable, and the vapors may have to be condensed. The return of condensate to the top, of course, increases the load on the stripper. Oil refineries frequently use relatively low boiling oil and strip with steam. To condense the oil vapors, steam must also be condensed and the water separated.

c. Stripping of Volatile Solvent with Its Own Vapor.—If a volatile solvent is used, the stripping is usually effected by the solvent vapor so that the stripper becomes, in effect, a distillation column and may be treated in the same fashion. The stripping section is identical. The reflux or dephlegmating section is of less importance than the enrichment section of the conventional still and may be reduced to a backward return condenser, or to an outside condenser and pump returning the condensate.

3. Distillation

a. Preliminary Considerations.—A liquid mixture may usually be separated into its pure components by fractional distillation, provided the boiling points of these components differ. Some liquid mixtures, however, form azeotropic or constant boiling mixtures with boiling points either above or below that of either of the pure components. These constant boiling mixtures behave in distillations as if they were pure components and may not be further separated by distillation under the same conditions. Distillation under vacuum or high pressure may be effective, or the addition of a third substance may permit separation (azeotropic distillation). The composition and boiling point of some of the more important constant-boiling mixtures are given in Table L-2 later in the chapter.

In the case of partly miscible liquids, two-phase constant-boiling mixtures are always obtained as the condensed overhead product of simple distillation. Although such mixtures can nearly always be separated by a combination of decantation and distillation, two columns are usually required for perfect separation.

Distillation may be conducted either as a batch or as a continuous process. Though batch distillation is advantageous for handling separation of small quantities of material, the continuous column distillation is more efficient and almost universally employed in the production of tonnage products. Consequently continuous distillation will alone be considered in this chapter.

A partial separation of liquids may be obtained by merely boiling and condensing the enriched vapors. For effective separation it is necessary to add a column and reflux to conduct a fractional distillation. For any given separation there is a minimum reflux which must be employed. The exact value of this minimum is, however, of little consequence, since in practice a larger reflux should be employed to keep the column height reasonable. The optimum reflux may be found by a balance of column height against column diameter and steam requirements.

A distillation column performs two functions. The stripping section below the feed plate must remove the volatile material from the bottom product, and the enrichment section above the feed plate must produce a volatile product of satisfactory purity. The requirements of the two sections may vary considerably. In particular, for a dilute feed, the steam required for stripping may be in considerable excess of that needed to supply the reflux for the enrichment section. In this case it is occasionally found advantageous to divide the operation into two columns, as is often done in the alcohol industry. The beer still, which is short and fat, strips the alcohol vapors from the slop, and the slightly enriched vapors are fed to the second column which produces the high-proof alcohol.

A recommended procedure for process design is as follows:

1. By the McCabe-Thiele or other method compute the reflux ratio required to give a reasonable number of theoretical plates.
2. Compute the steam and cooling water requirements.
3. Size the column.
4. Judge by results whether a different reflux ratio should be employed.

b. McCabe-Thiele Method for Computing Theoretical Plates.—This graphical method, though not exact, yields moderately accurate results from simple calculations. If the number of moles of vapor flowing up the column is everywhere the same, the method becomes exact. When the molal heat of vaporization of the low-boiling component is only slightly less than that of the higher boiling component, this condition is approximated. If the heats of vaporization differ greatly (such as in acetone–water mixtures), the method will not give entirely accurate results.

To use this method, the mole fraction, y, of the volatile component in the vapor is plotted against the mole fraction, x, of the same component in the liquid phase. Three lines are constructed. The equilibrium line is a plot of the equilibrium data. There are two operating lines: the *enrichment line* for the section above the feed plate and the exhausting or *stripping line* for the feed plate and below. The enrichment line represents the composition of the *vapor leaving* and the *liquid entering*. The stripping line represents the *vapor entering* and the *liquid leaving*. To construct these lines it is necessary to assume a reflux. It is frequently convenient to express the amount of reflux as the reflux ratio: moles of liquid condensate returned to moles of product withdrawn. This is the usual way of expressing reflux ratio. A more significant (though seldom used) expression is the ratio of moles reflux to moles of feed. When expressed in this fashion, the optimum reflux is more nearly independent of feed composition. If a very low reflux ratio is chosen, the operating lines may cut the equilibrium line. Such a condition indicates that a larger reflux ratio must be employed in order to accomplish the desired result. Often several reflux ratios must be tried to secure a balance between column height

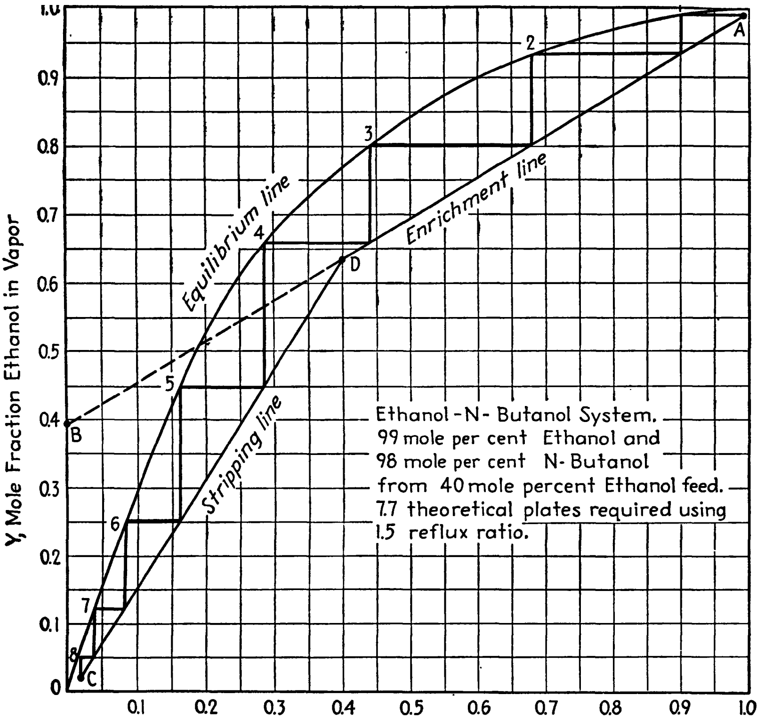

FIG. L-4.—McCabe-Thiele diagram for distillation.

and amount of boiling required. This method is illustrated by Example L-2 and Fig. L-4.

Example L-2. It is desired to distill 100 moles/hr of an ethyl alcohol–n-butyl alcohol mixture containing 40 mole per cent ethyl alcohol. 99 mole per cent ethyl alcohol and 98 mole per cent n-butyl alcohol are required. For first calculation assume a reflux ratio (reflux to product) of 1.50.

SOLUTION: This problem is solved in Fig. L-4 constructed as follows:

1. Equilibrium line drawn from data presented in Table L-8.

2. Enrichment line *AB*. Point *A* represents the composition of liquid entering vs. vapor leaving, *i.e.*, $x = y = 0.99$, the composition of the product.

Point *B*: $x = 0, \quad y = \frac{x_p}{R + 1} = \frac{0.99}{2.5} = 0.396$

where x_p = mole fraction of product = 0.99
R = reflux ratio = 1.5

$\left(\text{As constructed, the slope of the line is } \frac{1}{R + 1}\right)$

3. Stripping line *CD*. Point *C* represents the mole fraction of vapor entering vs. the liquid leaving. It is customary to take these both as the composition of the bottom product, *i.e.*, $x = y = 0.02$. *D* is the joint intersection of the two lines at $x = 0.40$, the feed composition.

4. Number of theoretical plates. Beginning with point *A*, the number of theoretical plates is stepped off by alternate horizontal and vertical lines. 7.7 theoretical plates are required, 3.3 above the feed plate and 4.4 below. This calculation tacitly assumes that the feed is preheated to its bubble point (initial boiling point) and that there are no control fluctuations. To allow for these factors, more theoretical trays should be allowed, say 4 above feed plate and 6 below, making a total of 10. If a 40 per cent plate efficiency is assumed, 25 actual plates will be required.

c. Other Methods.—As in the case of absorption and stripping, a plate-by-plate iteration (with material and heat balances at each plate) is the only precise manner of treating all cases, particularly for multicomponent distillations.

Lindsay and Baker[1] describe a modification of the McCabe-Thiele method which takes the difference between latent heats into account and is, therefore, capable of high accuracy. Smoker[2] gives an accurate algebraic method which unfortunately is rather cumbersome. Thompson and Beatty[3] and Colburn[4] give simplified algebraic procedures applicable to many cases. Faasen[5] gives a graphical method for estimating reflux ratios and theoretical plates from only the relative volatility. The relative volatility is nearly constant for systems that obey Raoult's law but may not be constant for other systems.

d. Heat and Cooling Requirements for Distillation.—These are computed by standard thermodynamic methods. Heat must be supplied to (1) heat the high-boiling constituent from the inlet temperature to the boiling temperature at the base of the column, (2) heat the volatile component from the feed temperature to its boiling point, (3) vaporize the volatile product and the reflux, and (4) supply the heat of solution, which is the net heat evolved when the two liquids are mixed without vaporization. Because the heat required depends on the temperature of the feed, it is frequently desirable to preheat the feed. This may conveniently be done by heat exchange between the feed and the hot liquid leaving the base, the steam condensate, or even the condensed product. Estimation of steam and cooling water demands is illustrated by Example L-3.

[1] *Ind. Eng. Chem.*, **35,** 418 (1943); cf. Peters, *Ind. Eng. Chem.*, **14,** 476 (1922).

[2] *Trans. Am. Inst. Chem. Engrs.*, **34,** 165 583 (1938).

[3] *Ind. Eng. Chem.*, **34,** 1124 (1942).

[4] *Ind. Eng. Chem.*, **33,** 459 (1941).

[5] *Ind. Eng. Chem.*, **36,** 248 (1944).

Example L-3. It is desired to find the steam and water requirements for the distillation discussed in Example L-2, *i.e.*, the separation of 100 moles/hr of an *n*-butyl alcohol–ethyl alcohol solution containing 40 mole per cent of ethyl alcohol using a 1.5 reflux ratio. For this calculation the separation may be assumed a perfect one.

SOLUTION:

1. Quantities involved,

Molecular weights:

n-Butyl alcohol = 74
Ethyl alcohol = 46
n-Butyl alcohol: 60 × 74 = 4,440 lb/hr
Ethyl alcohol: 40 × 46 = 1,840 lb/hr

2. Temperature at top of column is 175°F (boiling point of 99 mole per cent ethyl alcohol from Table L-8).

3. Temperature at base,

Allow 1.6 in. of water drop per plate, or 40 in. total.

$$\text{Pressure} = 14.7 + 40\,\frac{0.433}{12} = 16.4 \text{ psi}$$

Temperature of boiling *n*-butyl alcohol = 250°F (from Fig. E-17)

4. Approximate average column temperature is 201°F, at feed plate (boiling point of 40 mole per cent ethyl alcohol at 1 atm from Table L-8).

5. Temperature of feed, assume 185°F, this assumption to be justified later by calculation 12.

6. Sensible heat supplied to *n*-butyl alcohol, 185 to 250°F, at 212°F the specific heat is 0.78 Btu/(lb)(°F) (from Fig. E-15)

$$\Delta h = 4{,}440 \times 0.78(250 - 185) = 225{,}000 \text{ Btu/hr}$$

7. Sensible heat supplied to ethyl alcohol, 185 to 175°F (a drop in temperature),

Specific heat at 180°F is 0.78 Btu/(lb)(°F)(from Fig. E-15)

$$\Delta h = 1{,}840 \times 0.78(175 - 185) = -14{,}000 \text{ Btu/hr}$$

8. Heat of vaporization of ethyl alcohol,

$$\frac{\Delta H}{T} = 26.2 \text{ Btu/(lb mole)(°R)(from Fig. E-19)}$$

$$\Delta H = \frac{1{,}840}{46} \times (1 + 1.5) \times 26.2 \times (175 + 460)$$
$$= 1{,}664{,}000 \text{ Btu/hr } (1.5 = \text{reflux ratio})$$

9. Heat of solution, neglect as deviation from Raoult's law is small.

10. Total heat supplied,

$$225{,}000 - 14{,}000 + 1{,}664{,}000 = 1{,}875{,}000 \text{ Btu/hr}$$

This is exclusive of heat losses. Making an arbitrary allowance of 5 per cent for these, the total becomes 1,970,000 Btu/hr.

11. Steam required,
Assume steam supplied to the vaporizer at 25 psig.

$$\text{Temperature} = 267°\text{F}, \qquad \text{latent heat} = 934 \text{ Btu/lb (Table E-14)}$$

$$\text{Steam} = \frac{1,970,000}{934} = 2,110 \text{ lb/hr}$$

12. Heat exchange,
Assume preheat is supplied to feed by exchange with the *n*-butyl alcohol product. Heat supplied to heat feed from 80 to 185°F,

$$\begin{aligned} \Delta h &= 4,440 \times 0.66 \times (185 - 80) + 1,840 \times 0.69 \times (185 - 80) \\ &= 308,000 + 133,000 = 441,000 \text{ Btu/hr} \end{aligned}$$

Heat supplied by *n*-butyl alcohol,

$$-\Delta h = 4,440 \times 0.66 = 2,930 \text{ Btu/°F, temp. drop}$$

Temperature drop to supply needed heat,

$$-\Delta t = \frac{441,000}{2,930} = 150°\text{F}$$

Temperature of product leaving exchanger = 250 − 150 = 100°F.
(This makes a temperature difference of 20°F at the cold end of the exchanger.)

13. Cooling requirements,
Condenser removes 1,664,000 Btu/hr (calculation 8).
Product cooler cools alcohol from 175 to 90°F,

$$-\Delta h = 1,840 \times 0.69 \times (175 - 90) = 107,000 \text{ Btu/hr}$$

Total heat removed,

$$1,664,000 + 107,000 = 1,771,000 \text{ Btu/hr}$$

The quantity of water required will depend on the temperature rise which depends on cooling water vs. exchanger costs at plant site. Taking a 40°F rise the water required is

$$\frac{1,771,000}{40 \times 500} = 886 \text{ gpm}$$

DISCUSSION: 2,110 lb/hr of steam are required for the particular process design assumed. It would be desirable to repeat the calculation for different reflux ratios before adopting the final process design—comparing the resulting sizes of the column and exchanger, and the utility requirements. Also the heat loss should be estimated more explicitly.

To check on the accuracy of the calculation made in this example, the number of moles of vapor at the base may be computed. The heat of vaporization of *n*-butyl alcohol at 250°F is 25.3 × (250 + 460) = 18,000 Btu/lb mole; making the quantity vaporized = 1,970,000/18,000 = 109 mole/hr. This is only slightly more than the 100 moles vapor/hr at the top of the column. Thus, the condition of a constant molar vapor stream required for accuracy of the McCabe-Thiele method is nearly fulfilled. Further, since the error is in the direction of fewer theoretical plates, the calculation is conservative.

4. Equilibrium Data

a. Basic Laws of Solution.—A perfect solution is defined as one having the following three properties: (1) its volume is equal to the sum of the volumes of the constituents before mixing; (2) there is no heat liberated or absorbed on mixing the component liquids in any proportion; and (3) the mixture obeys Raoult's law, which is given below.

$$p_1 = p_1^0 x_1, \qquad p_2 = p_2^0 x_2, \text{ etc.} \tag{L-8}$$

where p_1, p_2 = partial pressure of components 1, 2 = py_1, py_2
p = total pressure, any units
p_1^0, p_2^0 = vapor pressure of components 1, 2, in pure state
x_1, x_2 = mole fraction of components 1, 2, in liquid
y_1, y_2 = mole fraction of components 1, 2, in vapor

If this law is obeyed, the other requirements of a perfect solution are almost invariably fulfilled and all the thermodynamic properties may be computed from those of pure constituents.

The use of Raoult's law in absorption and stripping calculations has already been mentioned (see Table L-1). It may, moreover, be used to compute a vapor-liquid equilibrium diagram from the vapor pressure of the two components. To do this, choose a temperature intermediate between the two liquids and secure p_1^0 and p_2^0, the vapor pressures of the component liquids.

$$p_1 = p_1^0 x_1$$
$$p_2 = p_2^0 x_2$$

but

$$p_1 + p_2 = p \qquad \text{and} \qquad x_2 = 1 - x_1$$

or

$$p = p_1^0 x_1 + p_2^0(1 - x_1)$$

and

$$x_1 = \frac{p - p_2^0}{p_1^0 - p_2^0} \tag{L-9}$$

and

$$y_1 = \frac{p_1^0 x_1}{p} \tag{L-10}$$

These quantities are defined as for Eq. (L-8).

Raoult's law usually applies to mixtures of very similar compounds such as benzene-toluene, pentane-hexane, ethyl alcohol–propyl alcohol mixtures. (However, it may fail for even these at high pressures and temperatures.)

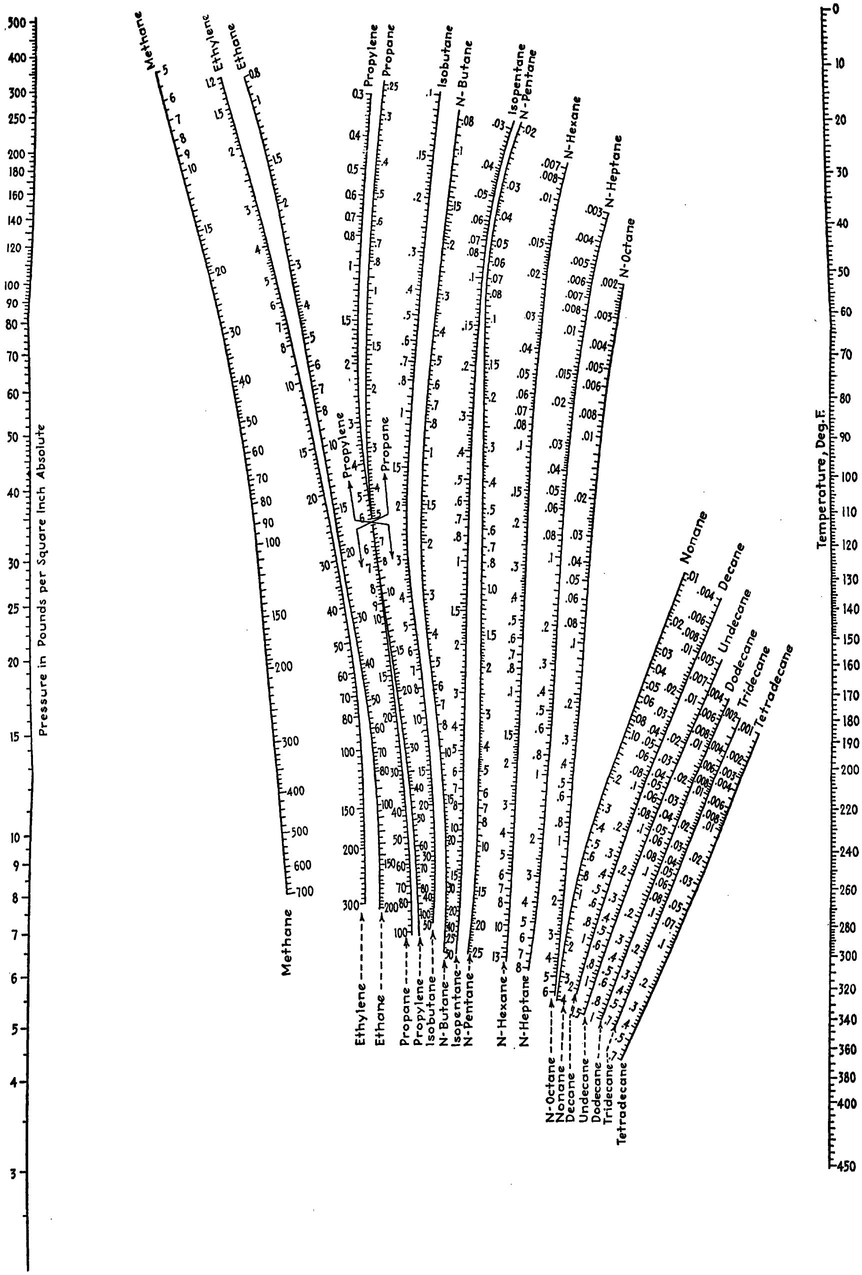

FIG. L-5.—Nomograph for equilibrium constants of hydrocarbons. [*Reprinted from Scheibel and Jenny, Ind. Eng. Chem.* **37**, 80 (1945). *By permission of the American Chemical Society.*]

Another law applicable when Raoult's law is inaccurate is Henry's law.

$$p_2 = Hx_2 \tag{L-11}$$

where p_2 = partial pressure of component 2
x_2 = mole fraction of component 2
H = Henry's law constant, same units as p_2

This usually applies only to comparatively dilute solutions unless Raoult's law is obeyed, when H becomes the vapor pressure of the pure component. Henry's law is frequently stated differently from the above. The Ostwald and Bunsen coefficients are proportionality constants between the concentration and the pressure, but the concentration is expressed as a volume ratio instead of as mole per cent. These coefficients are, roughly, proportional to the reciprocal of Henry's-law constant defined above.

Frequently, equilibrium data for hydrocarbons are given as the vaporization constant:

$$k_1 = \frac{y_1}{x_1}$$

where k_1 = vaporization constant for component 1 at specified temperature and total pressure
y_1, x_1 = mole fraction of component 1 at equilibrium for gas, liquid

This method of correlating data assumes that Henry's law is valid at any given temperature and total pressure. There are, of course, many other laws governing solutions to be found in modern treatises on physical chemistry.

b. Experimental Data.—For a limited number of systems these are given in the following pages. The data covered are listed below:

Vaporization constants of hydrocarbons	Fig. L-5
Data on constant boiling mixtures	Table L-2
Vapor—liquid boiling-point data:	
Acetic acid–water	Table L-3
Acetone–water	Table L-4
Acetone–methyl alcohol	Table L-5
Acetone–ethyl alcohol	Table L-6
Ethylene dichloride–toluene	Table L-7
Ethyl alcohol–*n*-butyl alcohol (cf. Fig. L-4)	Table L-8
Benzene–ethyl alcohol	Table L-9
Ethyl alcohol–water	Tables L-10 and L-11
Ethyl acetate–ethyl alcohol	Table L-12
Isopropyl alcohol–water	Table L-13
Vapor pressures of ammonia solutions	Tables L-14 and L-15
Solubility of gases in water	Table L-16

TABLE L-2.—COMPOSITION AND BOILING POINTS OF SOME CONSTANT BOILING MIXTURES AT ATMOSPHERIC PRESSURE
(Based on data from "International Critical Tables")

System		Mole % of *A*	Temp., °F	Maximum or minimum
Component *A*	Component *B*			
Acetone	Methyl acetate	61	133	Minimum
Acetic acid	Benzene	2.5	176	Minimum
	Toluene	62.7	222	Minimum
n-Butyl alcohol	Toluene	37	222	Minimum
Carbon tetrachloride	Ethyl alcohol	61.3	149	Minimum
	n-Propyl alcohol	75.0	163	Minimum
	Ethyl acetate	43.0	167	Minimum
	Methyl alcohol	44.5	132	Minimum
Carbon disulphide	Acetone	61.0	102	Minimum
	Ethyl alcohol	86.0	108	Minimum
	Methyl acetate	69.5	104	Minimum
	Methyl alcohol	72.0	100	Minimum
Chloroform	Acetone	65.5	148	Maximum
	Ethyl alcohol	84	139	Minimum
	Isopropyl alcohol	92	141	Minimum
Ethyl alcohol	Benzene	44.8	155	Minimum
	Ethyl acetate	46	161	Minimum
	Toluene	81	170	Minimum
Isopropyl alcohol	Benzene	39.3	162	Minimum
	Ethyl acetate	30.5	167	Minimum
	Toluene	77	177	Minimum
Methyl alcohol	Acetone	20	132	Minimum
	Benzene	61.4	137	Minimum
	Ethyl bromide	14	95	Minimum
	Ethyl chloride	62	139	Minimum
	Ethyl acetate	91.7	144	Minimum
	Methyl acetate	35	129	Minimum
Water	Ethyl alcohol	10.57	173	Minimum
	Formic acid	43.3	225	Maximum
	Hydrobromic acid	83.1	258	Maximum
	Hydrochloric acid	88.9	230	Maximum
	Hydrofluoric acid	65.4	248	Maximum
	Isopropyl alcohol	31.46	176	Minimum
	Nitric acid*	62.2*	249*	Maximum

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* At 14.23 psia pressure.

TABLE L-3.—VAPOR-LIQUID EQUILIBRIA, ACETIC ACID—WATER SYSTEM AT 1 ATM
[York and Holmes, *Ind. Eng. Chem.*, **34,** 348 (1942). By permission of the American Chemical Society]

Boiling temp., °C	°F	Water in liquid		Water in vapor	
		Weight %	Mole %	Weight %	Mole %
113.7	236.7	2.7	8.5	5.2	15.5
108.7	227.7	9.8	26.7	16.5	39.8
105.7	222.2	18.0	42.3	26.4	54.5
104.2	219.6	27.5	55.9	37.6	66.6
102.5	216.5	36.8	66.0	49.2	76.4
101.8	213.4	48.5	75.8	60.0	83.3
102.2	215.9	58.6	82.5	68.5	87.9
100 8	213.4	66.7	87.0	75.9	91.3

TABLE L-4.—VAPOR-LIQUID EQUILIBRIUM DATA FOR THE SYSTEM ACETONE–WATER AT 1 ATM
[Brunjes and Bogart, *Ind. Eng. Chem.*, **35,** 255 (1943). By permission of the American Chemical Society]

Temp., °F	Acetone in liquid		Acetone in vapor	
	Weight %	Mole %	Weight %	Mole %
133.7	99.50	98.40	99.65	98.44
133.9	99.20	97.47	99.35	97.93
134 2	98.85	96.38	99.10	97.15
134.6	98.00	93.83	98.60	95.62
135.9	97.50	92.37	98.30	94.72
135.7	96 70	90.04	97.90	93.53
135 9	95.40	86.55	97.40	92.08
136.7	93.65	82.08	96.80	90.37
136.9	91.20	76.29	96.20	88.71
137.8	89.50	72.57	95.90	87.90
137.9	87.40	68.29	95.65	87.23
138.9	84.20	62.32	95.20	86.03
139.8	78.60	52.28	94.85	85.12
139 8	77.00	50.96	94.90	85.24
140.5	72.00	44.39	94.50	84.21
141.6	58.20	30.85	94.00	83.09
144.9	40.20	17.27	93.10	80.73
149.4	29.75	11.64	91.85	77.77
161.8	18.00	6.38	87.30	68.09
185.3	6.80	2.21	72.40	44.88
197.6	3.60	1.15	55.50	27.91

Table L-5.—Vapor-liquid Equilibria for the System Acetone–Methyl Alcohol at 1 atm

(Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York, 1941)

Temp., °F	Acetone in liquid, mole %	Acetone in vapor, mole %
148.1	0	0
146.5	5.0	10.2
144.5	10.0	18.6
140.4	20 0	32.2
137.6	30.0	42.8
135.6	40.0	51.3
134.0	50.0	58.6
132.8	60.0	65.6
131.5	70.0	72.5
131.1	80.0	80.0
133.0	100.0	100.0

Table L-6.—Vapor-liquid Equilibria for the System Acetone–Ethyl Alcohol at 1 atm

(Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York, 1941)

Temp., °F	Acetone in liquid, mole %	Acetone in vapor, mole %
173.0	0	0
167.7	5.0	15.5
163.4	10.0	26.2
159.8	15.0	34.8
156.2	20.0	41.7
153.1	25.0	47.8
150.6	30.0	52.4
148.6	35.0	56.6
146.5	40.0	60.5
143.3	50.0	67.4
140.7	60.0	73.9
138.4	70.0	80.2
136.4	80.0	86.5
134.6	90.0	92.9
133.0	100.0	100.0

TABLE L-7.—EXPERIMENTAL VAPOR-LIQUID EQUILIBRIUM DATA FOR ETHYLENE DICHLORIDE–TOLUENE AT 1 ATM

[Jones, Schoenborn, and Colburn, *Ind. Eng. Chem.*, **35**, 666 (1943). By permission of the American Chemical Society]

Temp., °F	Mole fraction ethylene dichloride	
	Liquid x	Vapor y
188.8	0.812	0.909
190.1	0.784	0.893
194.3	0.700	0.844
197.9	0.585	0.765
198.8	0.568	0.750
204.6	0.479	0.674
204.8	0.446	0.645
206.3	0.415	0.614
208.1	0.375	0.578
210.7	0.365	0.565
213.4	0.252	0.424
215.6	0.235	0.401
224.6	0.100	0.197
226.1	0.045	0.095

TABLE L-8.—VAPOR-LIQUID EQUILIBRIUM DATA FOR THE SYSTEM ETHYL ALCOHOL–*n*-BUTYL ALCOHOL AT 1 ATM

[Brunjes and Bogart, *Ind. Eng. Chem.*, **35**, 255 (1943). By permission of the American Chemical Society]

Temp., °F	Ethyl alcohol in liquid		Ethyl alcohol in vapor	
	Weight %	Mole %	Weight %	Mole %
174.4	90.3	93.8	99.6	99.7
176.5	83.0	88.7	98.0	98.7
177.8	77.2	84.5	96.9	98.2
183.0	64.3	74.3	91.4	94.6
186.1	55.5	66.6	88.6	92.7
187.5	48.4	60.1	84.9	90.0
190.9	45.7	57.4	82.7	88.5
190.5	43.7	55.5	82.1	88.1
195.0	36.9	48.8	75.0	82.8
200.3	31.7	42.7	69.3	78.4
205.6	22.9	32.3	60.3	70.8
215.3	17.3	25.2	48.1	59.7
222.5	12.0	17.8	38.0	49.6
232.0	7.3	11.3	22.3	31.6
237.9	4.0	6.2	12.2	18.1

TABLE L-9.—VAPOR-LIQUID EQUILIBRIA FOR THE SYSTEM BENZENE–ETHYL ALCOHOL AT 1 ATM

(Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York, 1941)

Temp., °F	Benzene in liquid, mole %	Benzene in vapor, mole %
172.6	0	0
165.9	6	20
162.3	11	30
158.2	20	40
155.0	39	50
154.2	57	56
155.0	72	60
159.4	89	70
167.4	96	85
175.5	100	100

TABLE L-10.—VAPOR-LIQUID EQUILIBRIA OF SYSTEM ETHYL ALCOHOL–WATER UNDER PRESSURE

[Griswold, Haney, and Klein, *Ind. Eng. Chem.*, **35**, 701 (1943). By permission of the American Chemical Society]

Temp., °F	Mole % ethyl alcohol in liquid	Mole % ethyl alcohol in vapor	Pressure, psia
302	7.3	33.4	107
	13.8	41.4	119
	26.5	48.7	130
	51.4	61.6	145
	63.9	69.5	147
392	5.8	24.7	300
	11.4	33.8	331
	23.7	43.3	370
	49.7	58.5	415
	63.3	68.1	424
482	6.3	19.2	717
	11.1	26.8	766
	23.5	37.3	869
	50.7	54.9	977
	68.8	69.6	1,010
527	12.6	24.5	1,176
	26.0	34.4	1,341
	40.0	42.5	1,492

TABLE L-11.—EXPERIMENTAL VAPOR-LIQUID EQUILIBRIUM DATA FOR ETHYL ALCOHOL–WATER AT 1 ATM

[Jones, Schoenborn, and Colburn, *Ind. Eng. Chem.*, **35**, 666 (1943). By permission of the American Chemical Society]

Temp., °F	Mole fraction ethyl alcohol	
	Liquid x	Vapor y
212.0	0	0
203.9	0.018	0.179
195.1	0.054	0.3375
185.7	0.124	0.470
182.5	0.176	0.514
181.0	0.230	0.542
179.6	0.288	0.570
177.8	0.385	0.612
176.8	0.440	0.633
175.7	0.514	0.657
174.0	0.673	0.735
172.9	0.840	0.850
173.0	1.0	1.0

TABLE L-12.—VAPOR-LIQUID EQUILIBRIA FOR THE SYSTEM ETHYL ACETATE–ETHYL ALCOHOL AT 1 ATM

(Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York, 1941)

Temp., °F	Ethyl acetate in liquid, mole %	Ethyl acetate in vapor, mole %
173.0	0.0	0.0
169.9	5.0	10.2
167.9	10.0	18.7
165.0	20.0	30.5
163.1	30.0	38.9
161.8	40.0	45.7
161.3	50.0	51.6
161.3	54.0	54.0
161.4	60.0	57.6
162.0	70.0	64.4
163.4	80.0	72.6
166.5	90.0	83.7
168.8	95.0	91.4
170.8	100	100

TABLE L-13.—VAPOR-LIQUID EQUILIBRIUM DATA FOR THE SYSTEM ISOPROPYL ALCOHOL–WATER AT 1 ATM

[Brunjes and Bogart, *Ind. Eng. Chem.*, **35**, 255 (1943). By permission of the American Chemical Society]

Temp., °F	Isopropyl alcohol in liquid		Isopropyl alcohol in vapor	
	Weight %	Mole %	Weight %	Mole %
178.2	97.85	93.19	96.82	90.11
177.8	97.29	91.53	96.07	88.01
177.4	96.33	88.72	94.97	85.00
176.9	95.05	85.20	93.54	81.26
176.5	93.42	81.00	91.77	76.98
176.3	91.77	77.02	90.47	74.01
176.1	90.15	73.33	89.28	71.42
176.1	88.48	69.71	88.27	69.31
176.0	88.15	69.05	88.02	68.79
176.0	87.90	68.57	87.74	68.24
176.1	87.82	68.38	87.86	68.46
176.3	87.70	68.13	87.70	68.13
176.1	86.08	64.96	86.91	66.59
176.3	82.39	58.38	85.34	63.58
176.7	73.95	45.97	82.98	59.39
177.4	62.30	33.14	81.27	56.54
178.0	51.15	23.87	80.67	55.59
178.2	45.24	19.86	79.93	54.44
178.4	39.35	16.29	78.99	52.98
178.5	31.90	12.32	79.50	53.78
180.9	23.50	8.43	77.10	50.24
182.8	14.59	4.88	74.42	46.60
192.3	8.01	2.54	63.18	33.99
195.4	6.50	2.04	57.96	23.08
199.7	4.38	1.36	49.00	22.44
203.5	2.72	0.83	36.55	14.73
210.0	0.52	0.16	11.16	3.64

TABLE L-14.—TOTAL VAPOR PRESSURES OF AQUA AMMONIA
(Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York, 1941)
Psia

Temp., °F	Molal concentration of ammonia in the solutions in percentages										
	0	5	10	15	20	25	30	35	40	45	50
32	0.09	0.34	0.60	0.97	1.58	2.60	4.20	6.54	9.93	14.18	19.40
40	0.12	0.45	0.77	1.24	2.01	3.25	5.21	8.06	12.05	17.20	23.39
50	0.18	0.64	1.05	1.65	2.67	4.29	6.75	10.35	15.34	21.65	29.26
60	0.26	0.86	1.42	2.21	3.51	5.55	8.65	13.22	19.30	27.05	36.26
70	0.36	1.17	1.84	2.90	4.56	7.13	11.01	16.56	24.05	33.39	44.42
80	0.51	1.52	2.43	3.76	5.85	9.06	13.86	20.61	29.69	40.96	54.08
90	0.70	2.02	3.15	4.83	7.43	11.40	17.23	25.48	36.34	49.82	65.32
100	0.95	2.62	4.05	6.13	9.34	14.22	21.32	31.16	44.12	59.99	78.30
110	1.27	3.34	5.14	7.72	11.64	17.58	26.07	37.81	53.16	71.87	93.19
120	1.69	4.27	6.46	9.63	14.42	21.54	31.69	45.62	63.59	85.33	110.20
130	2.22	5.38	8.07	11.91	17.67	26.20	38.25	54.55	75.55	100.86	129.50
140	2.89	6.70	9.98	14.63	21.49	31.54	45.73	64.78	89.19	118.24	151.30
150	3.72	8.29	12.23	17.81	26.00	37.81	54.43	76.61	104.65	138.10	1[illegible]5.40
160	4.74	10.16	14.92	21.54	31.16	45.02	64.25	89.88	122.10	160.20	202.70
170	5.99	12.41	18.01	25.87	37.11	53.27	75.55	104.84	141.75	185.10	233.20
180	7.51	15.00	21.65	30.86	44.02	62.68	88.17	121.68	163.70	212.60	267.00
190	9.34	18.06	25.87	36.60	51.81	73.32	102.56	140.75	188.10	243.30	304.30
200	11.53	21.60	30.72	43.14	60.62	85.33	118.68	161.81	215.20	277.00	345.50
210	14.12	25.61	36.26	50.58	70.72	98.80	136.42	185.10	245.10	314.50	390.70
220	17.19	30.27	42.47	59.00	81.91	113.81	156.41	211.24	278.20	355.10	439.60
230	20.78	35.59	49.60	68.46	94.43	130.64	178.28	239.70	314.50	400.20	493.40
240	24.97	41.52	57.65	78.91	108.60	149.20	202.74	270.92	354.10	448.90	552.30
250	29.83	48.32	66.67	90.74	124.08	169.48	229.62	305.60	397.60	502.40	

TABLE L-15.—PARTIAL VAPOR PRESSURES OF WATER OVER AQUA AMMONIA
(Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York, 1941)
Psia

Temp., °F	Molal concentration of ammonia in the solutions in percentages										
	0	5	10	15	20	25	30	35	40	45	50
32	0.09	0.084	0.079	0.074	0.070	0.065	0.060	0.056	0.051	0.047	0.042
40	0.12	0.115	0.108	0.101	0.095	0.089	0.083	0.076	0.070	0.064	0.058
50	0.18	0.17	0.16	0.15	0.14	0.13	0.12	0.11	0.10	0.094	0.085
60	0.26	0.24	0.23	0.21	0.20	0.19	0.17	0.16	0.15	0.13	0.12
70	0.36	0.34	0.32	0.30	0.28	0.26	0.25	0.23	0.21	0.19	0.17
80	0.51	0.48	0.45	0.42	0.40	0.37	0.34	0.32	0.29	0.27	0.24
90	0.70	0.66	0.63	0.58	0.55	0.51	0.47	0.44	0.40	0.37	0.33
100	0.95	0.90	0.85	0.79	0.74	0.69	0.64	0.59	0.55	0.50	0.45
110	1.27	1.20	1.14	1.07	1.00	0.93	0.86	0.80	0.73	0.67	0.60
120	1.69	1.60	1.51	1.42	1.33	1.24	1.15	1.06	0.97	0.89	0.80
130	2.22	2.10	1.98	1.86	1.74	1.62	1.51	1.39	1.28	1.17	1.05
140	2.89	2.73	2.57	2.42	2.26	2.11	1.96	1.81	1.66	1.52	1.37
150	3.72	3.51	3.31	3.11	2.91	2.72	2.52	2.33	2.14	1.95	1.76
160	4.74	4.48	4.22	3.97	3.71	3.46	3.22	2.97	2.73	2.49	2.25
170	5.99	5.66	5.34	5.02	4.70	4.38	4.07	3.75	3.45	3.15	2.84
180	7.51	7.10	6.69	6.30	5.89	5.49	5.10	4.71	4.33	3.94	3.57
190	9.34	8.83	8.32	7.82	7.32	6.83	6.34	5.86	5.38	4.91	4.44
200	11.53	10.90	10.27	9.65	9.04	8.43	7.83	7.23	6.64	6.06	5.48
210	14.12	13.35	12.58	11.82	11.07	10.32	9.59	8.86	8.13	7.42	6.71
220	17.19	16.25	15.32	14.39	13.48	12.57	11.67	10.78	9.90	9.03	8.17
230	20.78	19.64	18.51	17.40	16.29	15.19	14.11	13.03	11.97	10.91	9.87
240	24.97	23.60	22.25	20.91	19.58	18.26	16.95	15.66	14.38	13.12	11.86
250	29.83	28.20	26.58	25.00	23.39	21.82	20.25	18.71	17.18	15.67	

TABLE L-16.—SOLUBILITY OF GASES IN WATER

(Abstracted from "Gas Engineers' Handbook," McGraw-Hill Book Company, Inc., New York, 1934)

BASIS: Standard cubic feet dissolved in 1 cu ft of water (corrected to 60°F) when saturated at a total pressure of 14.73 psi.

	Temperature, °F							
	32	50	68	86	104	122	140	176
Hydrogen sulphide, H_2S	4.84	3.52	2.63	2.04	1.62	1.29	1.02	0.514
Sulphur dioxide, SO_2	.....	54.8	37.5	26.2	18.5	12.8	9.43	4.10
Carbon dioxide, CO_2	1.79	1.24	0.898	0.672	0.519	0.405	0.308	
Carbon monoxide, CO	0.037	0.030	0.023	0.020	0.018	0.015	0.013	0.008
Methane, CH_4	0.058	0.044	0.034	0.028	0.023	0.020	0.017	0.010
Acetylene, C_2H_2	1.80	1.35	1.05	0.85				
Ethylene, C_2H_4	0.235	0.167	0.125	0.099				
Ethane, C_2H_6	0.103	0.068	0.048	0.036	0.028	0.023	0.018	0.010
Hydrogen, H_2	0.023	0.020	0.019	0.017	0.016	0.015	0.014	0.009
Atmospheric nitrogen, N_2	0.025	0.019	0.016	0.014	0.012	0.010	0.009	0.006
Oxygen, O_2	0.052	0.040	0.032	0.027	0.023	0.020	0.017	0.010

c. Heats of Solution.—The heat of solution of vapors is the sum of the heat of vaporization and the heat of mixing the two liquids at the temperature of interest. Frequently the latter may be neglected and the heat of vaporization alone used. Another rule for estimating the heat of solution is to employ the heat of vaporization at the saturation pressure corresponding to the total pressure at which the column is operating. This latter rule is applicable to gases above the critical pressure. Actually, neither rule is accurate for general application, and the true value frequently lies between the two. In some cases the heat of mixing of the liquids may be quite considerable and specific data must be consulted.

Table L-17 gives approximate heats of solution of hydrocarbons in absorption oils; Table L-18 gives the heat of mixing of ammonia and water.

TABLE L-17.—APPROXIMATE HEATS OF SOLUTION OF HYDROCARBON GASES IN 200 MOLECULAR WEIGHT OILS

No. carbon atoms in hydrocarbon	Heat of solution, Btu/lb mole	
	At 80°F	At 250°F
1	1500	−300
2	5500	3500
3	6500	5500
4	8500	6500
5	10,000	8000
6	12,500	9500

TABLE L-18.—INTEGRAL HEATS OF SOLUTION OF LIQUID AMMONIA IN WATER (Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York, 1941)

Per cent of ammonia by weight	Btu/lb of mixture	Btu/lb of ammonia
0	0	358.0
10	34.4	343.8
20	65.7	328.5
30	92.5	308.2
40	108.2	270.0
50	109.4	218.8
60	101.9	169.7
70	84.8	121.1
80	60.7	75.8
90	31.9	35.5
100	0	0

5. Sizing Tray Columns

a. Capacities of Tray Columns.—The size of a tray column is determined by numerous constructional details as well as by the properties and flows of process materials handled. Accordingly, equipment manufacturers should be consulted for the final design. Figure L-6 permits the approximate determination of the diameter required. This relation is based on a consideration of entrainment between plates and gives the maximum permissible capacity. It is advisable to recommend lower values for operating conditions, say, 50 to 75 per cent of the maximum for distillation, and 30 to 50 per cent for absorption columns under pressure.

Tray spacing is determined primarily by economic considerations but may be dictated by necessity for easy cleaning, or by the need of minimizing heat leak of columns operated at very low or fairly high temperatures.

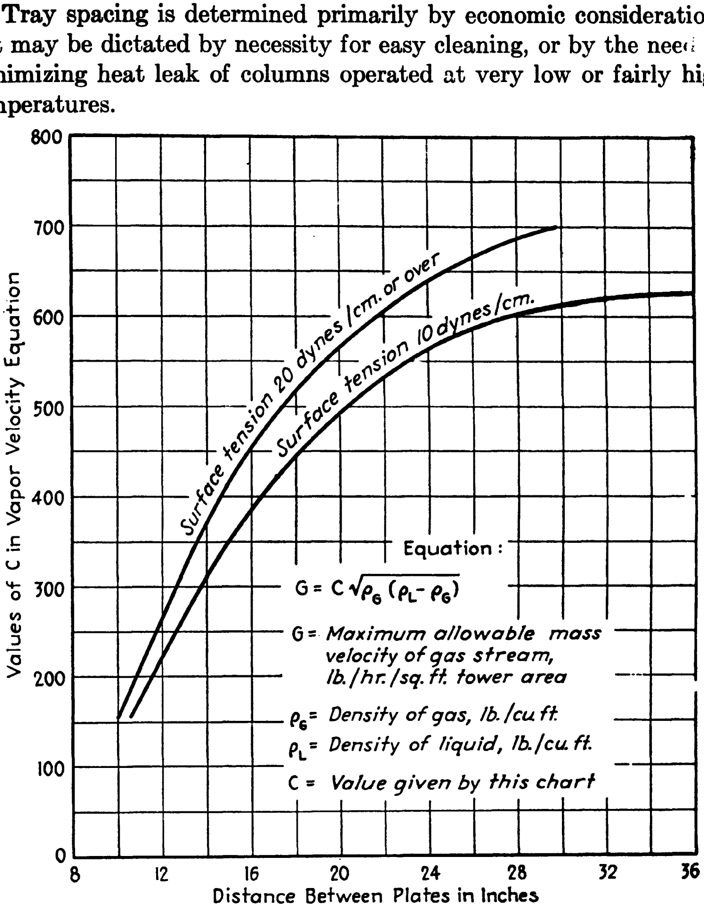

Fig. L-6.—Maximum capacity of tray columns. (*From Souders and Brown, Ref. Nat. Gaso. Mfr., February,* 1934.)

The liquid rate must also be taken into account in tower design, as higher liquid rates require greater skirt clearance and increased downspout area. Good, Hutchinson, and Rousseau[1] discuss the problem of liquid seals and skirt clearance. The downspouts may be sized by the Francis weir equation:

$$v = 0.4lh^{3/2}$$

where v = cfm overflow
l = perimeter of overflow pipe, in.
h = height of crest permissible, in.

The average width should be about three times the crest.

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[1] *Ind. Eng. Chem.,* **34,** 1445 (1942).

b. Number of Plates Required.—The over-all plate efficiency is the ratio of the number of theoretical plates to the number of plates actually required. If this plate efficiency is known and the number of theoretical plates can be computed, the number required may readily be determined. Actual efficiencies vary from a few to over 100 per cent. Estimates of 50 per cent for distillation and 25 per cent for absorption are conservative for most operations. Plate efficiency depends on column design as well as on the properties and rates of flow of the gas and liquid steams. Consequently, no simple rule for accurate prediction of plate efficiency is available. It has recently been found that the liquid viscosity is the predominant factor and that the performance of nearly a hundred commercial distillation and absorption columns could be correlated by the liquid viscosity. Although the resulting curve is reproduced in Fig. L-7 and may be used for preliminary estimates, the other factors should be considered in the final design. It will be noticed from this figure that low efficiencies may be expected from conventional plate columns handling viscous liquids. This suggests the desirability of special plate design or employment of other types of equipment, such as packed columns, for handling viscous liquids.

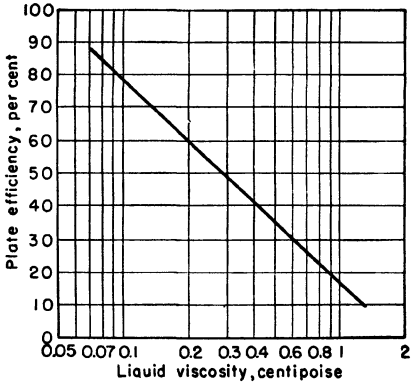


FIG. L-7.—Over-all efficiencies of plate columns. [*Drickamer and Bradford, Am. Inst. Chem. Engrs.* **39**, 319 (1943).]

6. Sizing of Packed Columns

a. Data on Common Packing Materials. Tables L-19 and L-20 give surface areas and other data on materials commonly used as filling in packed columns.

TABLE L-19.—PHYSICAL DATA ON DUMPED PACKINGS

Material	Dimensions, in.	Bulk density, lb/cu ft, tower volume	Surface area, sq ft/cu ft, tower volume	% free volume	No. pieces per cu ft, tower volume	Reference
Coke	3	24	12	50	......	1
	6	10	5.5	57	......	1
Ceramic Raschig rings	½ × ½	49	132	68	11,000	1
	1 × 1	45	58	68	1,330	2
	1½ × 1½	..	42	76	......	2a
	2 × 2	35	14	73	170	1
Metal Lessing rings	½ × ½	..	130	91	9,000	1
	1 × 1	..	74	93	1,300	1
	2 × 2	..	37	95	160	1
Berl saddles	½	..	97	63	......	2a
	1	..	60	71	......	2a
	1	42	79	69	2,300	2
	1½	..	50	70	......	2a

TABLE L-20.—PHYSICAL DATA ON STACKED PACKINGS

Material	Dimensions, in.	Bulk density, lb/cu ft, tower volume	Surface area, sq ft/cu ft, tower volume	% free space	% free transverse area	No. pieces per cu ft tower volume	Reference
Raschig rings	2 × 2	..	32	80	..	....	2a
	4 × 3	52	20	64	..	38	1
Partition rings	3 × 3	67	41	44	42	64	2
Single spiral rings	3 × 3	53	36	64	55	64	2
Triple spiral rings	3 × 3	60	42	57	56	64	2
Drip point grids (#6146, General Ceramic Co.)		72	18	48	41	9.2	2

1. Sherwood, "Absorption and Extraction," McGraw-Hill Book Company Inc., New York, 1937.

2. Molstad, Abbey, Thompson, McKinney, *Trans. Am. Inst. Chem. Engrs.*, **38**, 387 (1942).

2a. Tillson, *Trans. Am. Inst. Chem. Engrs.*, **38**, 405 (1942).

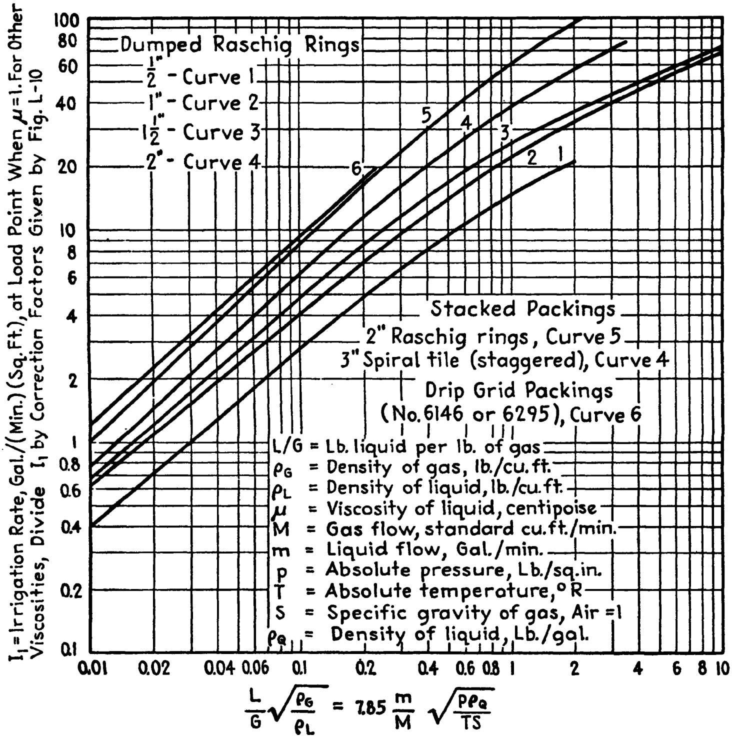
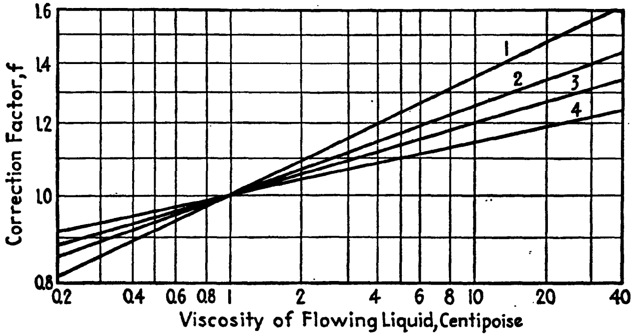


FIG. L-8.—Load points for columns packed with dumped Raschig rings or with stacked packings. [*Data of Tillson and of Molstad et. al., Trans. Am. Inst. Chem. Engrs.* **38** *387* (1942).]



Note: These factors differ from those frequently quoted.
They are best regarded as tentative

FIG. L-10.—Viscosity correction factors for liquid

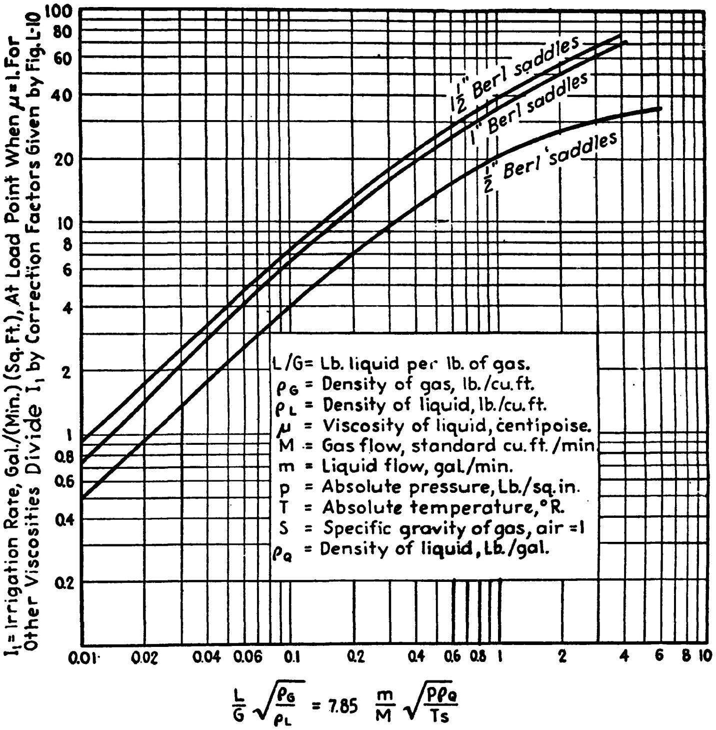


FIG. L-9.—Load points for columns packed with dumped Berl saddles. [*Data of Tillson on Berl saddles reported by Molstad et. al., Trans. Am. Inst. Chem. Engrs.* **38**, *387* (1942).]

Curve No.	Suggest for towers filled with:		
	Raschig Rings	Berl Saddles	Stacked Packings
1	½ inch		
2	1 inch	½ inch	
3	1½-2 inches	1 inch	Spiral tile
4		1½ inches	Grids

$I = fI_1$ = Irrigation rate at load Point. Where I_1 = load point irrigation based on 1 centipoise. See Fig L-8 and L-9 for numerical values

flow at load and flood points of packed columns.

b. Capacity of Packed Columns.—Obviously a column cannot be operated if there is danger of liquid being carried over by the gas stream. This danger is present if a column operates at or above the flood point either as defined by the graphical method of White[1] or as visually observed.[2] White further defined a lower limit, the load point, occurring when a further increase of gas flow increases the pressure drop by more than the second power of the superficial gas velocity. (The superficial gas velocity is the average velocity the gas would have if flowing through the cross section of the empty tower.) It is believed that, at flows below the load point, the liquid holdup is relatively independent of gas flow, but that this holdup is increased rapidly by gas flows above the load point. Accordingly, he suggests the load point as the upper limit for operation even though higher flows may be mechanically stable. Consideration of (1) possible control fluctuations, (2) possible future alteration of process design, (3) possible reduction in capacity because of settling and breakage of packing, and (4) difficulty of accurate prediction of load points under operating conditions, all suggest a more conservative capacity rating: say, 50 to 70 per cent of the load-point capacity. Colburn[3] suggests 50 per cent of the flood-point flows as a desirable operating condition. The choice between the flood point and the load point for rating is a matter of taste. In many instances the choice will be dictated by the type of data available.

Figures L-8 to L-10 (pages 410 and 411) permit the estimation of the load points for gases and nonfoaming liquids. These charts present the irrigation rate at the load point as a function of a term involving the liquid gas ratio, and the ratio of gas and liquid densities. With the exception of the viscosity term, the charts are a direct consequence of the correlation of Sherwood, Shipley, and Holloway.[4] The viscosity correction factors given in Fig. L-10 are based on the findings of later experimenters.[5]

In using these charts, it should be borne in mind that they are most accurate for air-water systems and may suffer somewhat from imperfections in the correlation for systems greatly different. The accuracy will, however, probably be within 20 per cent unless the process fluids are very unusual. *Very* low surface tension or fine suspended solids may possibly promote foaming and lower the tower capacity.

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[1] White, *Trans. Am. Inst. Chem. Engrs.*, **31**, 390 (1935).

[2] Sarchet, *Trans. Am. Inst. Chem. Engrs.*, **38**, 283 (1942).

[3] Colburn, Absorption of Gases by Liquids, Collected Papers on Teaching of Chemical Engineering, *Trans. Am. Inst. Chem. Engrs.*, 1940, pp. 269–281.

[4] Ind. Eng. Chem. **30**, 765 (1938).

[5] Bain and Hougen, *Trans. Am. Inst. Chem. Engrs.*, **40**, 29 (1944). Schoenborn and Dougherty, *Trans. Am. Inst. Chem. Engrs.*, **40**, 51 (1944).

c. Distribution of Liquid.—The problem of distribution of liquid flow through dumped packings has been studied by several experimenters, notably by Baker, Chilton, and Vernon[1] who conclude (1) that careful distribution of liquid at the top is essential, (2) that the ratio of tower diameter to packing size should be greater than 8:1, and (3) that, under these conditions, the liquid will not channel. Perhaps it is also well to give careful consideration to distribution of gas flow. It is believed that very low liquid rates should be avoided though little or no specific data are available on this point. Informal estimates run between 3 and 5 gpm/sq ft as the minimum irrigation for assured efficiency. Examples may be found in the literature of experimental columns operating with moderate efficiency at irrigations of 1 gpm/sq ft.[2] In the absence of specific data, these low rates should be used with caution. Probably liquid distribution is particularly important in this case, and operation near the load point may be desirable. Use of close-packed fillings such as the Stedman type[3] might be helpful.

d. Pressure Drop through Packed Columns.—The pressure drop in packed columns is very small, often smaller than the drop across the rest of the system. Table L-21 gives the range of pressure drops observed at the load point for several types of packing material.

TABLE L-21.—PRESSURE DROPS, PACKED COLUMNS AT LOAD POINT—AIR WATER
[Molstad et al., *Trans. Am. Inst. Chem. Engrs.*, **38**, 387 (1942)]

Packing	Range of Pressure Drop, In. of Liquid (Water)/Ft
½-in. Raschig rings	1.1–1.5
1-in. Raschig rings	0.6–1.8
1½-in. Raschig rings	0.4–0.5
2-in. Raschig rings	0.4–0.9
2-in. Raschig rings, stacked	0.2–0.5
½-in. Berl saddles	0.2–0.8
1-in. Berl saddles	0.7–1.2
1½-in. Berl saddles	0.5–0.6
3 × 3-in. single spiral tile, stacked staggered	0.3–0.6
Drip-point grid #6146, General Ceramic Co., straight flues	0.5–0.6

If a more accurate estimate of the pressure drop is required, it may be obtained by the use of equations of the following type:

$$\Delta p = \frac{U_0^n \rho^{n/2}}{(a - b\sqrt{L})^n} \quad \text{(equation applies below load point)}$$

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[1] *Trans. Am. Inst. Chem. Engrs.*, **31**, 296 (1935).

[2] White and Othmer, *Trans. Am. Inst. Chem. Engrs.*, **38**, 1067 (1942). Dwyer and Dodge, *Ind. Eng. Chem.*, **33**, 485 (1941). Duncan, Koffolt, and Withrow, *Trans. Am. Inst. Chem. Engrs.*, **38**, 259 (1942).

[3] U.S. Patent No. 2,047,444 (1936).

where Δp = inches water head/ft of packed length
U_0 = superficial gas velocity, fpm
L = irrigation rate, gpm/sq ft
ρ = gas density, flowing conditions, lb/cu ft
n = constant (1.8 to 2.0)
a, b = constants (b is somewhat dependent on viscosity)

Below are equations of this type for four packings:

1-in. Berl saddles:

$$\Delta p = \left(\frac{U_0}{105 - 11\sqrt{L}}\right)^2 \rho$$

1½-in. Berl saddles:

$$\Delta p = \left(\frac{U_0}{142 - 14\sqrt{L}}\right)^2 \rho$$

1½-in. Raschig rings:

$$\Delta p = \left(\frac{U_0}{130 - 13\sqrt{L}}\right)^2 \rho$$

No. 6146 drip grids, straight flues:

$$\Delta p = \left(\frac{U_0}{410 - 36.6\sqrt{L}}\right)^2 \rho$$

e. Height Required, Packed Columns.—There is need of a simple rule for estimating the height of packed length required to produce a desired result. The literature contains a great deal of scattered but valuable information on the subject, and frequently the reader may be able to find specific data on the system of interest, either in texts or in research papers. Dr. Molstad and his coworkers[1] present data on a number of packings in terms of a correlation suggested by Sherwood and Holloway.[2]

In absence of specific data, pilot-plant tests are strongly recommended. Rules of thumb may be employed for preliminary *guesswork*, say, 2 to 6 ft per theoretical plate or 1 to 3 ft as equivalent to a practical plate.

If a large number of theoretical plates or transfer units is required, reasonable heights per unit are probable. If only a few units are involved, however, the height may be determined largely by the gross amount of material and heat transfer involved. Unfortunately, much of the published tests are on dilute solutions for which thermal effects are small.

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[1] *Trans. Am. Inst. Chem. Engrs.*, **38,** 410, 605 (1942).

[2] *Trans. Am. Inst. Chem. Engrs.*, **36,** 39 (1940).

CHAPTER M

WATER

The water system in a plant is of prime importance. Cooling-water costs may even exceed steam costs. Corrosive water may dictate the use of expensive alloys throughout the plant. The literature on many phases of industrial water is extensive, though cooling water, as such, has not received the attention it deserves. This chapter gives brief mention of the various factors entering into process design and discusses cooling towers, water balance, and contact coolers in modest detail. Below is listed some useful reference material:

Babbitt and Doland, "Water Supply Engineering," 3d ed., McGraw-Hill Book Company, Inc., New York, 1939.

Partridge, "Formation and Properties of Boiler Scale," *Univ. Michigan Eng. Research Bull.* 15, 1930, Ann Arbor, Mich.

"Quality and Treatment of Water," American Water Works Association, New York, 1940.

Ryan, "Water Treatment and Purification," McGraw-Hill Book Company, Inc., New York, 1937.

Perry, "Chemical Engineers' Handbook," 2d ed., McGraw-Hill Book Company, Inc., New York, 1941.

Keenan and Kaye, "Thermodynamic Properties of Air," John Wiley & Sons, Inc., New York, 1945.

1. Water Quality and Treatment

Industrial water is used for a variety of purposes, a few of which are listed below:

1. Boiler feed water.
2. Process water (*i.e.*, water used in contact or to dissolve materials in process of manufacture).
3. Hot-water heaters.
4. Cooling engine and compressor jackets, or other hot surfaces to protect mechanical equipment.
5. General cooling water.

Treated water or condensate is nearly always used for boiler feed water. Very frequently this is also true of process water, particularly if it is used in distillation or for crystallization of high-purity products. Hot-water heaters and jacket cooling water sometimes require treated water. However, water of a total hardness of 50 ppm (expressed as $CaCO_3$) is usually satisfactory. The cost of treating general cooling water is usually excessive, and the whole plant must usually be designed to utilize the available supply even though it may be corrosive and excessively hard.

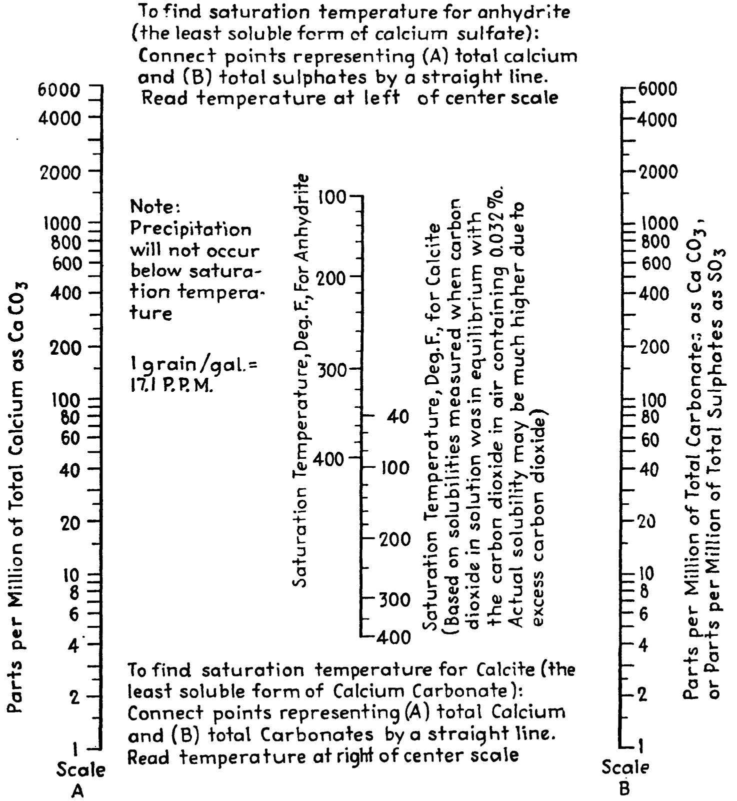
Because of the many complicated factors in quality of water, the empirical approach is probably the best; *i.e.*, to secure a water survey of quantities and analyses. If, by good fortune, the analysis is typical of waters in the locality, then scale and corrosion problems already encountered by existing plants afford a sound basis for water plant design.

Scale formation results from the precipitation of dissolved materials on the heating of water. Calcium sulphate, calcium carbonate, calcium hydroxide, magnesium hydroxide, and magnesium silicates are examples. Of these, calcium sulphate and carbonate are most troublesome in cooling-water service. Figure M-1 permits the estimation of solubilities of the least soluble forms of these two compounds in the absence of excess carbon dioxide. It is seldom possible to secure water that does not contain more calcium carbonate than represented by these solubilities because of the excess carbon dioxide that forms the soluble bicarbonate. This is not necessarily serious unless conditions favor rapid deposition. Sulphate hardness is usually rather troublesome. Where hard water must be employed, scale formation may be somewhat minimized by high velocity and by avoiding rapid heating. These effects can be more easily achieved by taking small temperature rises in the coolers. Keeping the maximum temperature low is also helpful.

Treatment of water is effected by one or more of five general methods:

1. Precipitation by adding chemicals (lime, soda ash, trisodium phosphate, etc.).
2. Ion exchange by inorganic zeolites.
3. Ion exchange by organic zeolites.
4. Addition of organic materials.
5. Distillation (steam condensate–multiple-effect evaporators).

Chemical precipitation removes most of the scale-forming materials but increases the total dissolved solids. Ion exchange by inorganic zeolites replaces calcium and magnesium ions by sodium. Ion exchange by organic zeolites may merely replace magnesium and calcium ions by sodium as in the case of inorganic zeolites. By a two-stage process, virtually all inorganic material other than silicic acid may be removed by organic zeolites, producing water comparable with distilled.[1] Addition of certain organic matter such as tannic acid, to some extent inhibits the formation of scale. Quebracho and similar materials are sometimes added to combat the phenomenon of caustic embrittlement in high-pressure boilers.[2] Steam condensate is nearly always available in plants and, if conserved, affords a supply of high-quality water. Multiple-effect evaporators produce very high-quality water and are used when the less expensive methods are unsuitable.


To find saturation temperature for anhydrite (the least soluble form of calcium sulfate): Connect points representing (A) total calcium and (B) total sulphates by a straight line. Read temperature at left of center scale

Note: Precipitation will not occur below saturation temperature

1 grain/gal. = 17.1 P.P.M.

To find saturation temperature for Calcite (the least soluble form of Calcium Carbonate): Connect points representing (A) total Calcium and (B) total Carbonates by a straight line. Read temperature at right of center scale

Parts per Million of Total Calcium as CaCO$_3$
6000
4000
2000
1000
800
600
400
200
100
80
60
40
20
10
8
6
4
2
1
Scale A
Saturation Temperature, Deg. F., For Anhydrite
100
200
300
400
40
100
200
300
400
Saturation Temperature, Deg. F., for Calcite (Based on solubilities measured when carbon dioxide in solution was in equilibrium with the carbon dioxide in air containing 0.032%. Actual solubility may be much higher due to excess carbon dioxide)
Parts per Million of Total Carbonates as CaCO$_3$, or Parts per Million of Total Sulphates as SO$_3$
6000
4000
2000
1000
800
600
400
200
100
80
60
40
20
10
8
6
4
2
1
Scale B

FIG. M-1.—Solubilities of calcite and anhydrite.

As some scale formation is almost inevitable, provision for its periodic removal from equipment should be made. The metaphosphates are suitable for this purpose, provided scale formation has not progressed too far. In some cases the use of corrosive acids or mechanical cleaning is necessary.

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[1] Nordell, *Chem. & Met. Eng.*, October, 1943, p. 112.

[2] Schroeder, Berk, and O'Brien, various papers in *Trans. Am. Soc. Mech. Engrs.* from 1934 on.

TABLE M-1.—PROPERTIES OF AIR MIXED WITH SATURATED WATER VAPOR (Adapted from Perry, "Chemical Engineers' Handbook," McGraw-Hill Book Company, Inc., New York, 1941)

°F	Saturated water vapor*		Volume, cu ft		Total heat† above 0°F, Btu.		
	Pressure, psi	Lb/lb dry air	1 lb dry air	1 lb dry air + vapor to saturate it	Of 1 lb dry air above 0°F	Of vapor to saturate 1 lb dry air	Total air + water vapor
0	0.0184	0.000781	11.58	11.59	0.0	0.84	0.84
4	0.0227	0.000963	11.68	11.70	0.96	1.03	1.99
8	0.0279	0.001183	11.78	11.80	1.93	1.27	3.20
12	0.0341	0.001447	11.88	11.91	2.89	1.55	4.44
16	0.0415	0.001764	11.99	12.02	3.86	1.90	5.76
20	0.0504	0.002144	12.09	12.13	4.82	2.30	7.12
24	0.0610	0.002596	12.19	12.24	5.79	2.78	8.57
28	0.0736	0.003134	12.29	12.35	6.75	3.36	10.11
30	0.0809	0.003444	12.34	12.41	7.23	3.69	10.92
32	0.0887	0.003782	12.39	12.47	7.72	4.06	11.78
34	0.0961	0.004100	12.44	12.52	8.20	4.40	12.60
36	0.1041	0.004452	12.49	12.58	8.68	4.77	13.45
38	0.1126	0.004809	12.54	12.64	9.17	5.17	14.34
40	0.1217	0.005202	12.59	12.70	9.65	5.60	15.25
42	0.1315	0.005625	12.64	12.76	10.14	6.07	16.21
44	0.1420	0.006078	12.69	12.82	10.62	6.55	17.17
46	0.1532	0.00656	12.74	12.88	11.10	7.08	18.18
48	0.1652	0.00708	12.79	12.94	11.58	7.65	19.23
50	0.1780	0.00764	12.84	13.00	12.07	8.26	20.33
52	0.1917	0.00823	12.89	13.07	12.55	8.91	21.46
54	0.2063	0.00887	12.95	13.13	13.03	9.61	22.64
56	0.2219	0.00955	13.00	13.20	13.52	10.36	23.88
58	0.2384	0.01028	13.05	13.26	14.00	11.16	25.16
60	0.2561	0.01105	13.10	13.33	14.48	12.00	26.48
62	0.2749	0.01188	13.15	13.40	14.97	12.92	27.89
64	0.2949	0.01276	13.20	13.47	15.45	13.89	29.34
66	0.3162	0.01370	13.25	13.54	15.93	14.93	30.86
68	0.3388	0.01471	13.30	13.61	16.42	16.03	32.45
70	0.3628	0.01578	13.35	13.69	16.90	17.21	34.11
72	0.3883	0.01692	13.40	13.76	17.38	18.47	35.85
74	0.4153	0.01813	13.45	13.84	17.87	19.81	37.68
76	0.4440	0.01942	13.50	13.92	18.35	21.24	39.59
78	0.4744	0.02080	13.55	14.00	18.84	22.76	41.60

TABLE M-1.—PROPERTIES OF AIR MIXED WITH SATURATED WATER VAPOR (*Continued*)

°F	Saturated water vapor*		Volume, cu ft		Total heat† above 0°F, Btu.		
	Pressure, psi	Lb/lb dry air	1 lb dry air	1 lb dry air + vapor to saturate it	Of 1 lb dry air above 0°F	Of vapor to saturate 1 lb dry air	Total air + water vapor
80	0.5066	0.02226	13.60	14.09	19.32	24.38	43.70
82	0.5406	0.02381	13.65	14.17	19.80	26.11	45.91
84	0.5767	0.02547	13.70	14.26	20.29	27.95	48.24
86	0.6148	0.02723	13.75	14.35	20.77	29.90	50.67
88	0.6551	0.02910	13.80	14.45	21.25	31.98	53.23
90	0.6977	0.03109	13.86	14.55	21.74	34.19	55.93
92	0.7427	0.03320	13.91	14.65	22.22	36.55	58.77
94	0.7901	0.03544	13.96	14.75	22.71	39.06	61.77
96	0.8401	0.03783	14.01	14.86	23.19	41.72	64.91
98	0.8929	0.04036	14.06	14.97	23.67	44.54	68.21
100	0.9486	0.04305	14.11	15.08	24.16	47.56	71.72
105	1.101	0.0505	14.24	15.39	25.37	55.95	81.32
110	1.274	0.0593	14.36	15.73	26.58	65.74	92.32
115	1.470	0.0694	14.49	16.10	27.79	77.16	104.95
120	1.692	0.0813	14.62	16.52	29.00	90.52	119.52
125	1.941	0.0953	14.75	16.99	30.21	106.2	136.41
130	2.221	0.1114	14.88	17.53	31.42	124.6	156.02
135	2.536	0.1305	15.00	18.13	32.63	146.2	178.83
140	2.887	0.1532	15.13	18.84	33.85	171.9	205.75
145	3.280	0.1800	15.26	19.64	35.06	202.4	237.46
150	3.716	0.2122	15.39	20.60	36.27	239.1	275.37
160	4.739	0.2987	15.64	23.09	38.69	337.8	376.49
170	5.990	0.4324	15.90	26.84	41.12	490.8	531.92
180	7.51	0.6577	16.16	33.04	43.55	749.2	792.75
190	9.34	1.0985	16.41	45.00	46.97	1255.7	1302.67
200	11.53	2.2953	16.67	77.24	48.40	2623.0	2671.40

---

* Below 32°F, the pressure of saturated vapor in contact with ice is given.

† The total air + water vapor added by author.

2. Cooling-tower Theory

Cooling towers remove heat from water largely by evaporation of water that is carried off by air. The amount of water vapor that can be carried off by a given quantity of air depends on its initial water-vapor content and its exit temperature. The latter determines the maximum quantity of water vapor in the exit air. The water-vapor content of air is usually determined by the familiar wet- and dry-bulb temperatures. Figure M-2, page 422, permits the estimation of the dew-point temperature and the relative humidity of air from the wet- and dry-bulb temperatures.

Table M-1, pages 418–419, gives the thermodynamic properties of air at atmospheric pressure, both as dry air and as air saturated with water vapor; it is also useful for air containing less water vapor than at saturation. Regardless of humidity, the total heat content of air and vapor will be that of saturated air at the *wet-bulb* temperature of the air in question. Similarly, the moisture content of air is specified by the *dew-point* temperature. The specific volume of wet air cannot be obtained from Table M-1 unless the air is saturated. However, the total volume may be obtained by additions of the specific volume of dry air and the volume contributed by the moisture. The latter contribution may be computed by the following equation:

$$V_w = (18.6 + 0.0405t)W$$

where V_w = volume contributed by moisture, cu ft/lb dry air
t = temperature (dry-bulb), °F
W = lb water vapor/lb air

Example M-1 is presented below to illustrate the use of Fig. M-2 and Table M-1 in cooling-tower calculations.

Example M-1. Find the amount of air required to cool 100 gpm of water from 95 to 80°F. The air enters at 78°F dry bulb, 70°F wet bulb, and leaves at 80°F saturated.

SOLUTION:

1. Heat removed from water 95 to 80°F,

$$100 \times 500 \times 15 = 750{,}000 \text{ Btu/hr}$$
$$(1 \text{ gpm} = 500 \text{ lb/hr})$$

2. Heat removed by 1 lb air (heat contents from Table M-1),

Heat content exit, 80°F saturated.......	43.70 Btu/lb
Heat content inlet, 70°F wet bulb.......	34.11
Heat removed from water............	9.59 Btu/lb dry air

3. Pounds of dry air required,

$$\frac{750{,}000}{9.59} = 78{,}200 \text{ lb/hr}$$

4. Moisture content inlet air,

$$\begin{aligned} \text{Dew point} &= 66°\text{F} \qquad \text{(from Fig. M-2)} \\ \text{Moisture content} &= 0.0137 \text{ lb/lb} \quad \text{(from Table M-1)} \end{aligned}$$

5. Specific volume of inlet air,

$$\text{Dry air at } 78°\text{F} = 13.55 \text{ cu ft/lb} \qquad \text{(Table M-1)}$$

$$\begin{aligned} \text{Moisture} &= (18.6 + 0.0405 \times 78) \times 0.0137 = (18.6 + 3.15) \times 0.0137 \\ &= 21.75 \times 0.0137 = 0.30 \text{ cu ft/lb dry air} \\ \text{Total} &= 13.55 + 0.30 = 13.85 \text{ cu ft/lb} \end{aligned}$$

6. Volume inlet air,

$$\frac{78{,}200 \times 13.85}{60} = 18{,}100 \text{ cfm}$$

7. Water evaporated,

Exit air at 80°F saturated carries.......	0.02226 lb/lb dry air
Inlet air at 66°F dew point carries......	0.01370
Net gain..........................	0.00856 lb/lb dry air

or

$$78{,}200 \times 0.00856 = 669 \text{ lb/hr}$$

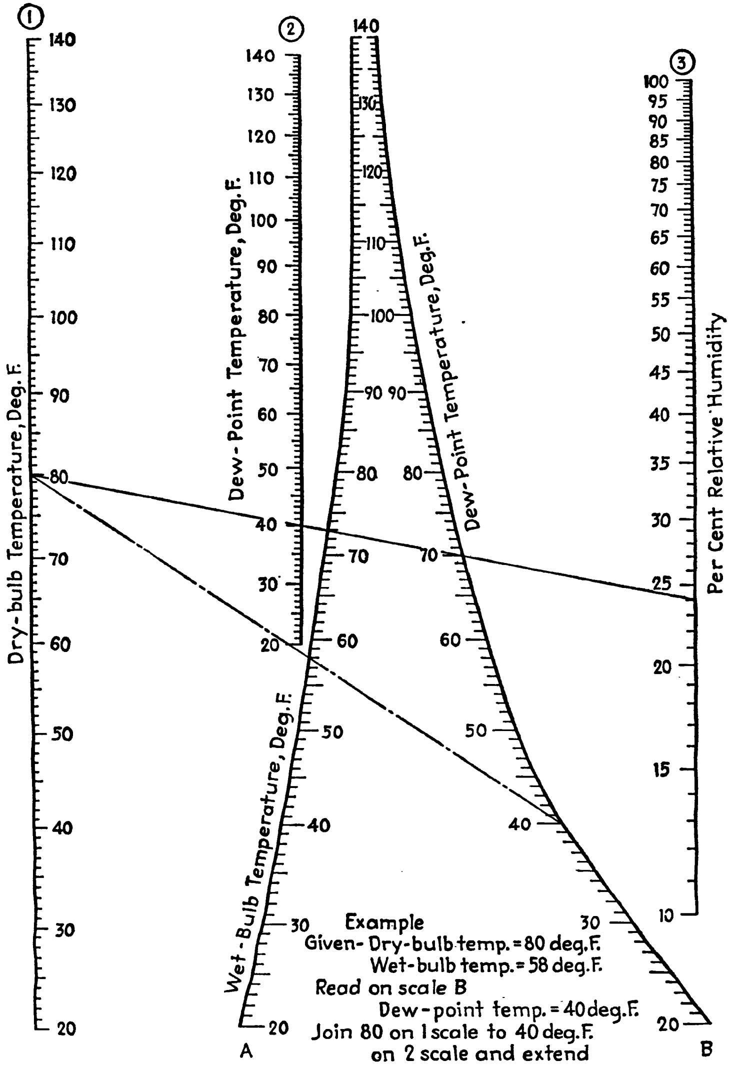
or

$$\frac{669}{500} = 1.34 \text{ gpm}$$

The water lost by evaporation may be computed as in the example above, but this accuracy is seldom required. The loss is generally between 0.9 and 1 per cent of effluent water for every 10°F through which the water is cooled.

As in the case of absorbing and stripping towers, the height of a cooling tower is related to the number of theoretical plates. However, special methods are used by tower designers.

Because of evaporation in cooling towers, the concentration of dissolved salts is increased; consequently, cooling water may not be circulated indefinitely and a sufficient portion must be discarded and replaced by fresh water to keep the quality up to standard. Usually discard of about 10 per cent of the water leaving the cooling tower is satisfactory; however, the amount discarded will depend on the quality of the fresh supply and on the temperature range of the cooling tower. Example M-2, page 423, illustrates these factors.


①
Dry-bulb Temperature, Deg. F.
140
130
120
110
100
90
80
70
60
50
40
30
20
②
Dew-Point Temperature, Deg. F.
140
130
120
110
100
90
80
70
60
50
40
30
20
Wet-Bulb Temperature, Deg. F.
Dew-Point Temperature, Deg. F.
140
130
120
110
100
90
80
70
60
50
40
30
20
A
B
③
Per Cent Relative Humidity
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10

Example
Given- Dry-bulb temp. = 80 deg. F.
Wet-bulb temp. = 58 deg. F.
Read on scale B
Dew-point temp. = 40 deg. F.
Join 80 on 1 scale to 40 deg. F.
on 2 scale and extend
to read 24 on 3 scale

FIG. M-2.—Relation between dry bulb, wet bulb, and dew point, and dry bulb, dew point, and relative humidity. (*By E. Cowan, Power, March*, 1934.)

Example M-2. A cooling tower cools 2,000 gpm from 90 to 80°F. 200 gpm of this is discarded after usage. The fresh water used for make-up has the following analysis:

Hardness, 250 ppm as $CaCO_3$
Alkalinity, 180 ppm as $CaCO_3$
Chlorides, 20 ppm as Cl
Sulphates, 25 ppm as SO_3

Find the average analysis of water leaving the cooling tower.

SOLUTION:

1. Evaporation loss,

Assume 1% for 10°F.................. 20 gpm

2. Windage loss,

Assume 1%.......................... 20

3. Make-up water,

To replace discard	200
To replace evaporation loss	20
To replace windage loss	20
Total	240 gpm

4. Concentration factor:

Solids contained in 240 gpm must leave with discard and spray, *i.e.*, in 200 + 20 = 220 gpm; therefore, concentration will be increased by factor of $^{240}/_{220} = 1.09$

5. Average analysis at cooling-tower exit,

Hardness, 1.09 × 250	273 ppm
Alkalinity, 1.09 × 180	196 ppm
Chlorides, 1.09 × 20	22 ppm
Sulphates, 1.09 × 25	27 ppm

6. Scale-forming tendencies. Assume that hardness is all due to calcium. From Fig. M-1, it will be seen that the water is not completely safe with respect to carbonate hardness but is safe for sulphate hardness. As the dissolved salts are only 9 per cent more than the make-up water, the quality is only slightly inferior to the fresh-water supply.

3. Weather Data

The performance of cooling towers is dependent on the local weather. Figure M-3, giving the design of wet-bulb temperatures for the United States, is based on an extensive survey and is reliable for open country. In very hilly or mountainous country, local variations may have to be taken into account. In any event a comparison of the local temperature with near-by weather stations will (in conjunction

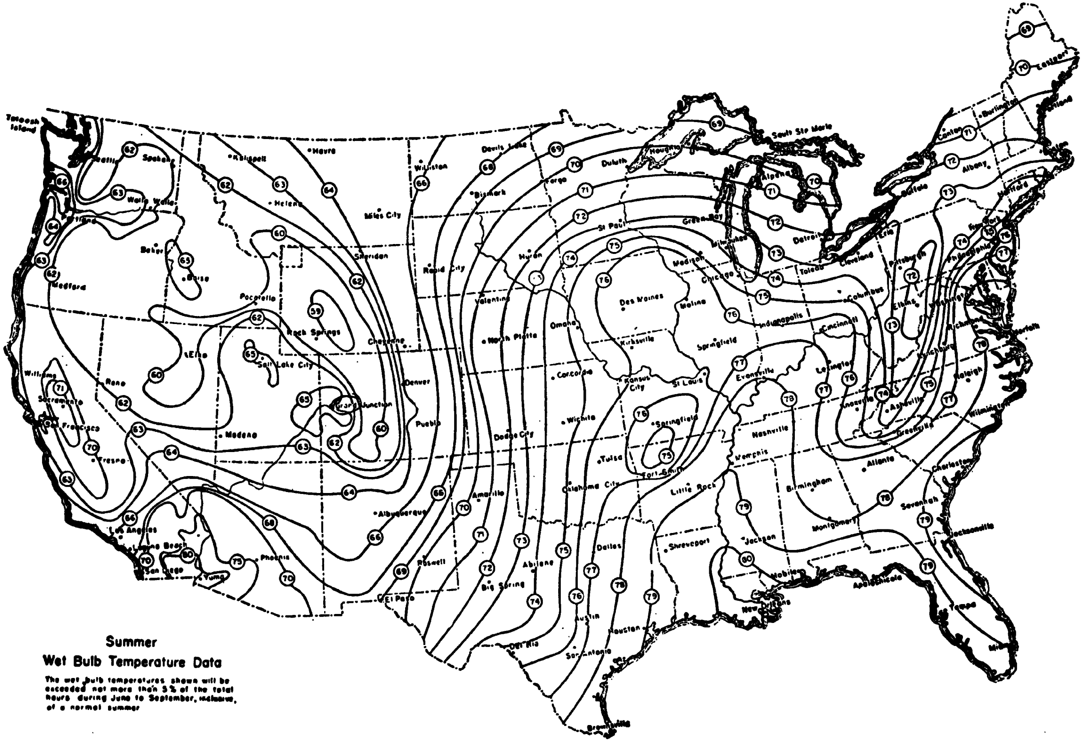


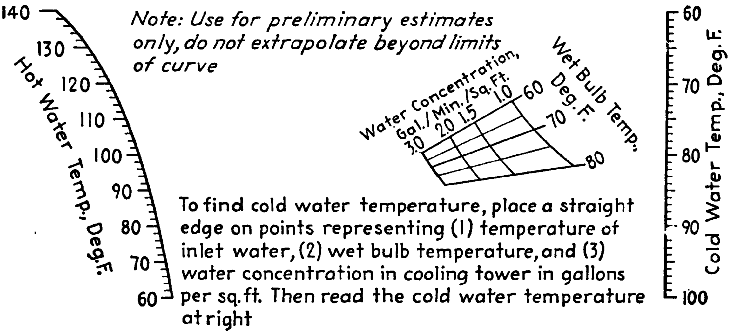
FIG. M-3.—Summer wet-bulb-temperature data. (*Courtesy of The Marley Company, Inc.*)

with Fig. M-3) permit the choice of a wet-bulb temperature adequate for design.

Wind velocities are subject to wide local variations. A 3-mph velocity is usually safe for design factors based on the minimum. Maximum wind velocities determine the mechanical strength necessary in the construction of cooling towers and, for that matter, of all equipment and buildings. To a small extent, cooling-tower performance depends on the atmospheric pressure. Altitude largely determines the barometric pressures (see Fig. C-1). Winter temperatures are important in regard to freeze-up problems.

4. Cooling Towers and Spray-pond Performance

Cooling towers may secure contact of water and air either by natural draft or by mechanical draft. Natural-draft towers are sometimes constructed with chimneys to increase the air flow, but they usually depend largely on the velocity of the prevailing wind. Because of variations in direction and velocity of the wind, their performance is somewhat changeable. However, if the tower design is adequate for the most unfavorable conditions, the resulting variation in water temperature is seldom serious enough to produce difficulty in process control. The use of fans to produce mechanical draft gives somewhat steadier performance and reduces the sizes required where space is limited. The fans may be placed either at the base or the top of the tower. Spray ponds are frequently used where spray loss is not serious and where their performance meets the service demands. Performance data are given as follows:



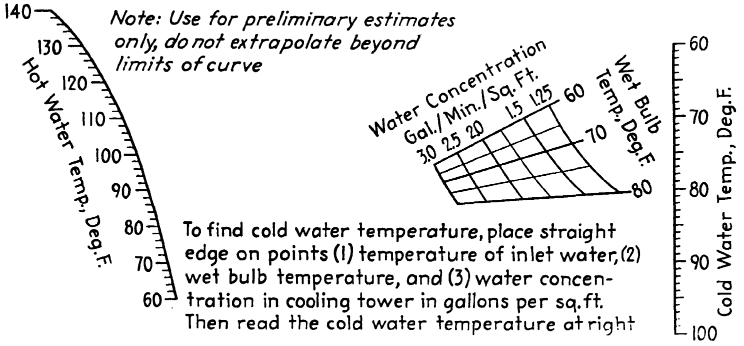
Note: Use for preliminary estimates only, do not extrapolate beyond limits of curve

To find cold water temperature, place a straight edge on points representing (1) temperature of inlet water, (2) wet bulb temperature, and (3) water concentration in cooling tower in gallons per sq. ft. Then read the cold water temperature at right

FIG. M-4.—Performance curve of a 12-deck, 35-ft-high atmospheric cooling tower at a wind velocity of 3 mph. (*By permission, The Fluor Corp., Ltd.*)

An atmospheric cooling tower	Fig. M-4
An induced-draft cooling tower	Figs. M-5 and M-6

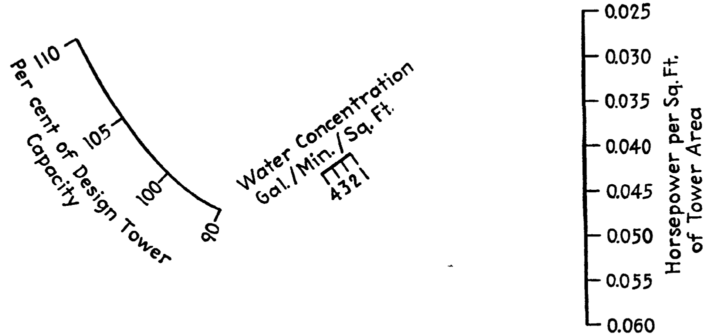
These are not adequate for mechanical design but are suitable for an intelligent choice of temperatures for preliminary process design and for estimating space requirements prior to quotations from the manufacturer. Cooling towers should be kept reasonably distant from other equipment that might be corroded by the spray.



Note: Use for preliminary estimates only, do not extrapolate beyond limits of curve

To find cold water temperature, place straight edge on points (1) temperature of inlet water, (2) wet bulb temperature, and (3) water concentration in cooling tower in gallons per sq.ft. Then read the cold water temperature at right

Fig. M-5.—Performance curve of a counter-flow, induced-draft cooling tower containing 24 ft of filling. (*By permission, The Fluor Corp., Ltd.*)



Note: Use for preliminary estimates only.

To find fan horsepower requirements, place straight edge at 100% on design tower capacity curve and at water concentration used in Fig.M-5, fan horsepower requirement shown multiplied by total tower area (as found in Fig.M-5) will give total horsepower requirements.

Fig. M-6.—Fan-horsepower curve for induced-draft cooling towers with 24 ft of filling. (*By permission, The Fluor Corp., Ltd.*)

5. Water Balances

The principles involved in making balances on plant water are best given by illustration. An idealized water balance, given in Table M-2, is based on the following assumptions:

1. Treated water or condensate is used for all boiler feed and process water except contact coolers.
2. Treated water is used in engine jackets, with closed recirculation and cooling by exchange with cooling-tower water. Only pump leakage and similar losses to be made up by treated water. These losses are assumed to be 2 per cent of the amount circulated.
3. 1,000 gpm of fresh water is available at 72°F. Some of this will be treated for boiler use, etc., the remainder to be used in services requiring the coldest available water. Finally, this water will go to the cooling tower.
4. Additional cooling-water requirements to be supplied by cooling-tower water. The cooling tower is assumed to supply 85°F water when the feed is 100°F.

TABLE M-2.—AN IDEALIZED WATER BALANCE
All figures in gpm
Fresh-water Balance

Treated water used:		
Boiler feed	72	
Process water	112	
Engine jackets	8	
Total	192	
Less condensate returned	52	
Total water to treatment plant		140
Fresh water for cooling		770
Total fresh water required		910
Installed capacity		1,000
Overage		90

Cooling-tower Balance

	Service		
	Supplied	Returned	Lost or discarded
85 to 90°F	1,200	1,200	0
85 to 100°F	4,300	4,210	90
85 to 105°F	1,500	1,300	200
85 to 110°F and above	300	0	300
Subtotals	7,300	6,710	590
Evaporation loss	......	.....	108
Spray loss	......	.....	72
Totals	7,300	.....	770
Installed capacity	10,000		
Fresh water	......	.....	770
Overage	2,700	.....	None

The water balance is, of course, affected by the temperature rises taken throughout the plant. Only small rises can be taken for some purposes, for example, for ammonia condensers. Large ones may be taken in other cases such as in stills, where the product cooler, vent cooler, and condenser may be placed in series. Consequently, no general rule can be given. The average rise should be consistent with good cooling-tower design. If very hard water is employed, small temperature rises are recommended.

6. Contact Coolers

Because heat-transfer coefficients of gases are frequently low, it is sometimes desirable to cool gases in a tower by direct contact with water or other liquid. Although either tray or packed towers may be employed, the latter are generally preferred for this service. Barometric condensers are essentially contact coolers, and the same construction is suitable for quenching hot gases. Contact coolers may be employed for any pressure service, provided the gas being cooled does not have too high a solubility in the cooling liquid. The principles used in estimating these towers are the same as for cooling water towers.

Published information on the performance of contact coolers is very meager. Parekh,[1] however, has studied the cooling of air at atmospheric pressure by water in a column packed with Raschig rings. Using an empirical correlation of his results together with the definition of the transfer unit, the following equation has been developed. To what extent this data can be extrapolated to gases of different specific gravity, and to pressures other than atmospheric, cannot be stated. The heights required, however, are usually low so that large factors of safety may frequently be employed without incurring unduly high costs.

$$Z = a(H_T - H_B)\left[\frac{\ln(\Delta H_B/\Delta H_T)}{\Delta H_B - \Delta H_T}\right]\sqrt{\frac{G}{L}} = a\frac{H_T - H_B}{\Delta H_m}\sqrt{\frac{G}{L}}$$

where Z = height of packing required, ft
H_T = heat content of exit gas and water vapor, Btu/lb of dry gas
H_B = heat content of inlet gas and water vapor, Btu/lb of dry gas
$\Delta H_T = H_T^* - H_T$
$\Delta H_B = H_B^* - H_B$

---

[1] Quoted by McAdams, "Heat Transmission," 2d ed., McGraw-Hill Book Company, Inc., New York, 1942. Some other data are also presented, and the definition of transfer units based on heat transferred is given.

H_T^* = heat content of gas saturated with water vapor at the inlet water temperature, Btu/lb of dry gas

H_B^* = heat content of gas saturated with water vapor at the exit-water temperature, Btu/lb of dry gas

ΔH_m = logarithmic mean of ΔH_T, ΔH_B

G/L = lb of dry gas per lb of water circulated

a = 1.4 for 1-in. Raschig rings
= 1.7 for 1½-in. Raschig rings
= 2.1 for 2-in. Raschig rings

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